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Historical Geology

Physical Geology. *By* Chester R. Longwell, Adolph Knopf, *and* Richard F. Flint. Third Edition.

Historical Geology. *By* Carl O. Dunbar.

Outlines of Physical Geology. *By* Chester R. Longwell, Adolph Knopf, *and* Richard F. Flint. Second Edition.

Outlines of Historical Geology. *By* the late Charles Schuchert *and* Carl O. Dunbar. Fourth Edition.

Outlines of Geology. Outlines of Physical Geology and Outlines of Historical Geology in one volume.

Rocks and Rock Minerals. *By* the late Louis V. Pirsson. *Revised by* Adolph Knopf. Third Edition.

Glacial Geology and the Pleistocene Epoch. *By* Richard F. Flint.

ANIMALS

1. *Tyrannosaurus*
2. *Trachydon*
3. *Triceratops*
4. *Struthiomimus*
5. *Ankylosaurus*
6. *Pteranodon*

PLANTS

7. Sedges
8. Conifer
9. Ginkgo
10. Palm
11. Willow
12. Live-oak
13. Dogwood
14. Sassafras
15. Laurel
16. Magnolia

YALE PEABODY MUSEUM.

Late Cretaceous Landscape in Wyoming

This scene of some seventy-five million years ago shows the dinosaurs in their heyday amidst flowering plants of the time. Part of a great mural by Rudolph Zallinger.

Historical Geology

By

Carl O. Dunbar

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Preface

The history of the Earth is a *drama* in which the actors are all real, and the stage is the whole wide world. The student must sense the action and feel the essence of high adventure in this *march of time* as shifting scenes unfold and living actors cross the stage. This viewpoint has controlled both the selection and the treatment of subject matter in this volume. No effort has been spared in preparing the illustrations to make the story vivid, and no extraneous material has been allowed to break its continuity, from the fiery birth of the planet to the unfolding of our modern world. The *prologue,* in four chapters, is intended to set the stage and to insure understanding of the principles used in interpreting the Earth's history.

The *appendix* was prepared for students who enroll in geology without previous training in biology. For such beginners the history of life on the Earth can have little meaning until they have learned something of the structure and relationships of at least the major groups of animals and plants. For several years Yale students have been required to study the material embraced in the appendix as an outside assignment during the first weeks of the course. Upon beginning the study of the Paleozoic era, each is required to pass a sight test showing that he can recognize the major groups of animals and plants. This treatment has been eminently satisfactory.

The subject matter of historical geology is inherently diversified, involving as it does certain aspects of astronomy, anthropology, and biology, as well as geology. The danger exists, therefore, that the beginner will feel bewildered by the mass of unfamiliar facts drawn from such widely different fields and, in the welter of details, will lose sight of the grand conceptions. For this reason we have tried to group all details about great principles. Believing it to be more important for the student to learn *how* a geologist thinks about the Earth than *what* he thinks about any particular detail, we have taken pains to emphasize principles of interpretation rather than to catalogue facts about the history of the Earth, appealing thus to understanding rather than to memory.

Stratified rocks with their entombed fossils form a manuscript in stone and are the source of much of our knowledge of the past history

of the world. It must be confessed, however, that stratigraphic descriptions are dull and detailed unless related to the physical history they record. The late Ordovician formations in New York State, for example, might appear to have no more than purely local interest; but when they are viewed as parts of a piedmont and coastal plain that was growing westward into an inland sea while the eastern border of the continent was rising into mountains, they take on significance. Therefore, in treating of each period of geologic history, we have tried at the outset to help the student visualize the physical geography of the time and understand the major physical changes our continent was undergoing. The panels of paleogeographic maps were designed as an aid to this end.

These panels are newly prepared from Professor Schuchert's latest, unpublished maps. The clouds have no meteorologic significance; they are merely a device to hide critical areas for which evidence is lacking or inconclusive. Just criticism has sometimes been made of paleogeographic maps which show no distinction between well-documented portions and those that are based entirely on inference. This is an attempt to avoid that shortcoming. These maps are, of necessity, highly generalized, and in most instances they indicate the maximum extent of the seas within a given epoch rather than the exact outline at any particular moment of time.

Correlation tables, omitted from the first printing, have now been added, in response to numerous requests, as Appendix B (pages 549–554). In their preparation full use has been made of the correlation charts published by the Committee on Stratigraphy of the National Research Council to which footnote references are made in appropriate places in the text.

To avoid the monotony inherent in the systematic account of period after period, emphasis is varied from chapter to chapter. In discussing the Cambrian, for example, considerable space is devoted to paleogeography and to the bases for subdividing the rocks into series and formations; in the Ordovician chapter, the Taconian orogeny is discussed at length because it illustrates the principles used in recognizing and dating all later orogenic disturbances. In this way, general principles of interpretation are developed one after another in the early chapters, leaving room in later ones for greater detail. This we believe to be fitting, since human interest in the rocks and the fossils increases as we approach the modern world.

The collateral readings suggested at the end of each chapter are intended for the interested student who would like to pursue the

subject further, not for the specialist or the professional geologist. For this reason, highly technical works are not listed, however important they may be from the professional point of view.

The facts of historical geology are drawn from many sources, and most of them are common knowledge. We have made no attempt to give credit for such general information except to cite works on subjects that are controversial and others so new that they may not be generally known to teachers of geology. Such references bear exponents in the text, referring to numbered citations at the end of the chapter.

This volume is a successor to, and an outgrowth of, the *Textbook of Historical Geology* by Schuchert and Dunbar. It preserves the same point of view and the same general organization except for the introductory chapters which are arranged so as to bring the geologic time scale near the front. The text of the previous work has been largely recast to take account of advances in knowledge or to make a more effective presentation. Special care has been given to the illustrations, many of which are new. The "bleed cuts" will speak for themselves.

In the preparation of this volume friendly assistance has been received from many sources. It is not possible to mention them all specifically, but my thanks are none the less real. Among those to whom I am most particularly indebted are my colleagues, Chester R. Longwell, Richard F. Flint, Adolph Knopf, Joseph T. Gregory, and John Rodgers, whom I have consulted on various problems in their several fields; G. Edward Lewis of the United States Geological Survey, who helped with the chapter on Mammals; Cornelius Osgood, chairman of the Department of Anthropology at Yale, who read and criticized the chapter on Man as it stood in the previous volume by Schuchert and Dunbar; W. W. Rubey, with whom I discussed plans for the book during the memorable days we spent aboard the U.S.S. *Panamint* on the way to Bikini. Others too numerous to mention have written to offer suggestions or to reply to inquiries about specific details. It is a pleasure to acknowledge all this friendly help, but, since none of those mentioned has read the manuscript in its final form, the writer alone must assume the responsibility for any shortcomings or mistakes.

The illustrations are from many sources, all of which are gratefully acknowledged in the credit lines attached to individual figures. The frontispiece and Figs. 165, 190, 203, and 216 are portions of a great mural in Peabody Museum, painted by Rudolph Zallinger

under the direction of the scientific staff. My cordial thanks go also to other members of the museum staff: particularly, to Shirley P. Glaser, who drew several of the new text figures; to Percy A. Morris, who made nearly all the photographs of fossils in the museum; to Sally H. Donahue, for her faithful help in the long and tedious preparation of the manuscript; and to Clara M. LeVene, for her indispensable aid in the final editing of the work and the preparation of the index.

To Charles Schuchert my obligation is unbounded. At his feet I learned much of what appears here as my own. His association was a constant stimulus, and his memory is an abiding inspiration.

Carl O. Dunbar

New Haven, Connecticut
October, 1948

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I. PROLOGUE

Chapter 1

RECORDS IN STONE

"There rolls the deep where grew the tree,
O Earth what changes hast thou seen!
There where the long street roars hath been
The stillness of the central sea."

—Tennyson.

Paleogeography: A Study in Ancient Lands and Seas

Evidence of Ancient Seaways. If North America were depressed 600 feet, the Mississippi Valley would be a great inland sea, the present Coastal Plain would be transformed into sea floor, and Florida into a submarine bank (Fig. 1). Over these submerged areas sediment would spread, burying sea shells, sharks' teeth, and occasional bones of porpoises and whales, while beach gravel and barnacles and oyster banks would accumulate along the shore zone.

If later the continent were uplifted, the sea would of course disappear, but these marine deposits would still form a telltale record of the submergence, and by plotting them on a map we could restore more or less accurately the limits of the vanished seaways. Figure 1 visualizes such an hypothetical submergence of North America. Figure 2 shows its actual counterpart in Malaysia, which was long a part of the Asiatic mainland but in recent geologic time has been submerged about 200 feet, flooding the lower parts to form South China and Java seas. Drowned valleys of the streams that once crossed these lowlands can still be traced on the sea floor. The large animals of Borneo, Sumatra, and Java migrated from Asia across this intervening lowland before it was submerged.

Submergences as great as that suggested above for North America have actually occurred many times in the past, either because of a general rise of sealevel or because of downwarping of the continent

itself, and the outlines of land and sea have thus varied widely from age to age.

Data for Restoring Lost Lands. Sediments accumulate locally on piedmont slopes or valley floors, or in basins on the lands, and they commonly have distinctive characteristics, such as mud cracks, footprints, skeletons of land animals, fossil land plants, or coal. Such

FIG. 1. Southeastern portion of North America as it would appear if depressed 600 feet. The deeply shaded area would then be shallow sea; the black areas, deep sea.

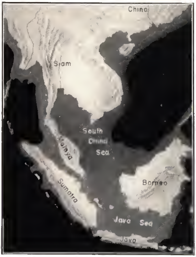


FIG. 2. Malaysia, a portion of southeastern Asia that has been partly submerged within the near geologic past. Adapted from Van Riel.

nonmarine deposits are clear evidence of a land surface, and, if those of a given geologic time are plotted, a minimum measure of the extent of the land area may be had. Fossil animals and plants may even indicate the approximate altitude and the climatic conditions under which the beds were deposited. A striking example of this was recently described from Kashmir Valley high in the Himalayas, where, at an elevation of 10,600 feet, plant-bearing deposits yielded a species of laurel that still inhabits India but lives only below an altitude of 6000 feet and in localities of subtropical temperature. It is clear that the region was much lower and warmer when these plant beds were formed.

Since a land mass is constantly exposed to the forces of erosion, the sediments that accumulate on its surface are eventually reworked

and carried into the sea, except where they have been downwarped or downfaulted below sealevel. Even marine strata, however, may throw much light on the position and character of the land from which they were derived. During transport, the sediment is size-graded, the coarsest material always coming to rest first, while progressively finer detritus is carried farther and farther. Hence, if a mass of strata grades from fine in one direction to coarser in another, it is evident that the ultimate source lay in the direction of increasing coarseness. Plotting of such data for the beds of a given age may indicate the approximate position and extent of the lands; and where a mass of strata shows changes from marine to nonmarine deposition, the approximate shoreline of the time may be drawn.

In most of the late geologic formations the application of these criteria is obvious, for they point to sources in land masses that are still supplying sediments. When applied to many of the ancient formations, however, they indicate highlands which no longer exist, and in some instances the results are surprising. The San Onofre conglomerate of California, for example, increases in coarseness toward the west in such a way as to indicate a source of its coarse boulders in highlands west of the present shoreline. There is confirming evidence, however, for some of these boulders are of peculiar types of metamorphic rock that are unknown on the mainland but do crop out on Catalina Island, some 40 miles off shore. The inference is that the islands west of southern California are remnants of a larger land mass that stood high while the San Onofre conglomerate was forming, and has since foundered.

Of course, high relief and heavy rainfall result in rapid erosion and relatively coarse detritus; lowlands, on the contrary, supply only fine mud or minerals in solution, and warm moist climate leads to thorough chemical decay. Critical study of the sediments may therefore indicate not merely the position of land masses but also their relative height and the type of climate that prevailed during long-past geologic ages.

Vestiges of Mountains. The growth and decay of a mountain range are recorded in the rocks long after the mountains themselves have disappeared. The nature of the evidence is indicated in Fig. 3. Block *A* represents the region before disturbance; it is formed of flat-lying bedded rocks with a low land at the right and shallow sea at the left. Uplift is under way in block *B*, and the strata at the right are being buckled into low folds. Streams are beginning to intrench them-

selves in the higher parts, and the old mantle of fine and well-decayed sediment is being stripped off and transported to the sea, where it is spread again as layers of marine mud. Thus far there is but little

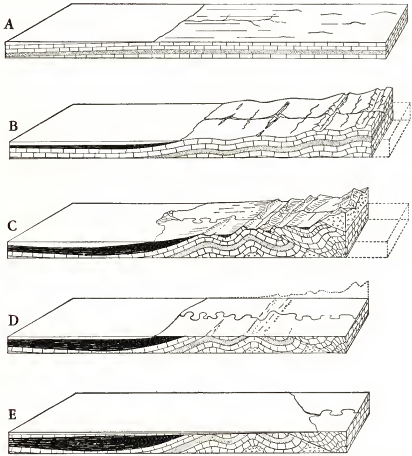


Fig. 3. Five stages in the rise and decay of a mountain range. Sediments derived from erosion of the range, and deposited in the geosyncline at the left, are shown in black. Length of section, some tens of miles.

sand and gravel because the streams still have low gradient. Block *C* represents a later stage after strong folding and faulting have produced rugged relief in the mountain region, and rapid erosion is loading the stream with sand and gravel as well as mud. Upon reaching the shore zone the streams are overloaded and tend to build an aggraded coastal plain extended locally into deltas. Meanwhile, as com-

monly occurs, the uplift in the mountain region is counterbalanced by sinking of the floor of a near-by geosyncline (*left*), and here the sediment derived from the mountains comes to rest, the gravel and coarse sand near shore and the finer sand and mud farther out. Block *D* shows a later stage after the region of uplift has been peneplaned. The mountains have now vanished, and sluggish streams meander across a lowland, carrying only the finest sediment. The cycle is complete in block *E* as the region is again submerged, and shallow sea creeps in over the site of the vanished highlands to bury the roots of the mountains with layers of fine mud or limestone.

At the surface all traces of the mountains are now gone; but underground there are records of two sorts, one where the mountains stood and another where their debris accumulated. If the region is uplifted and dissected at some later date, these records will be brought to light. In the area of disturbance a profound unconformity will separate the post-orogenic strata from the buried roots of the mountains, whose truncated folds and faults may indicate the nature of the disturbance and something of the size of individual folds and fault blocks. In block *E* of our hypothetical case, for example, it is evident that the folds were open to the left of a major thrust and that to the right of it the strata were more severely mashed and deformed. It would be quite simple in such a case to count the major folds, restore the missing parts, and determine their approximate dimensions. The date of the disturbance is clearly later than the youngest strata involved in the deformation, and earlier than the beds next above the unconformity.

A very different, but complementary, record is found in the area of deposition at the left (*black*). In so far as the debris of the destroyed mountain range accumulated here, the volume of the detrital sediment bears a definite relation to the size and height of the range. Fossils in these deposits will record the geologic date at which uplift and erosion were taking place, and obviously the coarsest part of the sedimentary record will correspond in time with the most rapid erosion and the greatest relief in the uplifted area. In the region of deposition the growth of the range is reflected in increasing coarseness and ever wider spread of the sands and gravels, and its decline is betrayed by a return to deposits of finer and finer grain. Hence, if the region of deposition were available for study, it would still be possible to infer much about the position and size of the uplift and to date it in geologic time, even if the site of the ancient mountains remained covered, or

was repeatedly disturbed until the early record was obscured, or if it foundered beneath the sea.

To apply this reasoning to a specific case, consider the sedimentary deposits of mid-Late Cretaceous date * which are plotted in Fig. 4. They clearly record a vast interior sea that extended from the Gulf of Mexico to the Arctic Ocean. In the eastern part the Cretaceous formations are of fine-grained shale with some interbedded chalky limestone; but toward the west they thicken and coarsen, including along the western margin vast deposits of sandstone with local conglomerates. Clearly the source of this material was chiefly from the west, and it must have been a highland of considerable ruggedness. Furthermore, as we approach the western margin, the rocks contain land plants and dinosaur bones, and locally have much interbedded coal. This must represent a swampy coastal lowland between the mountains and the sea. The enormous volume of the detrital Cretaceous rocks in this region shows that the land to the west was mountainous or was repeatedly uplifted. The land to the east of the sea, on the contrary, was low and flat, contributing but little sediment to the inland sea. By the application of such principles we can restore the major features of North America as they existed during Late Cretaceous time some 80 to 90 million years ago—a continent separated by a vast strait into two land masses, the eastern broad and low, the western narrow and mountainous.

Fig. 4. Map of North America as it was in mid-Late Cretaceous time. Present outcrops of Cretaceous rocks of this date are shown in solid black. Inferred seaways are shown in deep shading, and an area of fluvial deposits is indicated by horizontal black lines. Deep sea is shown in black with an overlay of white lines.

The reconstruction of ancient lands and seas is the science of *paleogeography* (Gr. *palaios*, ancient, + geography), and the inferred restorations (for example, Fig. 4) are *paleogeographic maps*.

* The Geologic Time Chart on page 19 shows the time relation of this period of Earth's history.

The Geologic Column: A Manuscript in Stone

Human history was not made in one country, nor could it be fully determined in a single continent. The locus of great events has shifted from age to age—from the Orient to Egypt, to Greece, to Rome, and finally to western Europe and America. It was necessary to consult manuscripts and materials from many parts of the world and *to fit the pieces of evidence together in the proper chronological order* before the history of mankind could be told.

Earth history, likewise, must be garnered from the geologic records in widely scattered parts of the world, and these records must be pieced together in their proper sequence. In the study of a local region the succession of rock formations is commonly presented diagrammatically as a *columnar section* (Figs. 5, 148), representing the formations as they would appear in a well core, the oldest at the bottom and younger ones in sequence toward the top. The composite record for the whole world may in similar fashion be constructed by superposing the major rock units from different parts of the world in the form of the *geologic column.* Its counterpart is the *geologic time chart* (Fig. 8) in which major units of geologic time are arranged to correspond with the geologic column. It serves as a framework about which the history of the Earth is developed. The principles used in building up the geologic column and the time chart now deserve attention.

Superposition. Since sedimentary rocks originate as loose sediment spread layer upon layer, it is evident that in any normal section the oldest bed is at the bottom, and each in turn is younger than the one on which it rests. This simple and self-evident principle is the *Law of Superposition.*

In disturbed areas, of course, the normal succession may be locally inverted, as in the lower limb of an overturned fold, or it may be interrupted, or duplicated, by faults; but such abnormalities will betray themselves in evidences of disturbance and in an unnatural sequence of fossils (next paragraph). Therefore, in a general study of a region of relatively simple structure, the sequence of beds can readily be ascertained by the order of superposition.

Faunal Succession. Most formations of sedimentary rock include fossil remains of the animals and plants that lived while the sediments were accumulating. The *assemblage* of animal species living together at a given time and place constitutes a *fauna;* the corresponding as-

semblage of plants is a *flora*. Thus the animals that now inhabit a region constitute a modern fauna, and the assemblage recorded by fossils in a bed of stratified rock constitutes an older fauna that lived while the rock was forming.

Just before 1800 William Smith, studying the Jurassic rocks of England, discovered that each formation has a distinct fauna, unlike those above or below. He also discovered that the characteristic fauna of any formation can be found in outcrop after outcrop as it is traced across the countryside, and so the characteristic fossils serve as a *guide* or *index* to distinct formations which he could recognize in any outcrop, without the necessity of careful tracing. Vast experience, accumulated since the days of Smith, has shown that this is a principle applicable to fossil-bearing rocks generally, and it is therefore one of the most important discoveries ever made in geology, since it permits us to identify rocks of the same age in different outcrops and even in widely separated areas, and so to piece together the fragmentary record.

William Smith did not know why each formation possesses a distinct fauna; his inference was based solely on study of a region of richly fossiliferous (fossil-bearing) rocks where the strata dip gently and the order of superposition is self-evident. We now know, of course, that different kinds of animals and plants have succeeded one another in time because *life has continuously evolved;* and inasmuch as organic evolution is world wide in its operation, only rocks formed during the same age could bear identical faunas.

Where the structure of the rocks is simple, the succession of faunas that occupied the region from age to age can be determined by studying the fossils of successive formations.

When this succession has been confirmed by wide experience in many regions of undisturbed strata, we may be confident that different forms of life succeeded one another in this order in time on the Earth. Therefore, the appearance of trilobites and dinosaurs and three-toed horses is not fortuitous and irregular; each lived only at a certain time in geologic history, and each is found fossil only in a certain part of the geologic column. The relative time of existence of a vast number of kinds of animals and plants has now been established, and their place in the geologic column has been confirmed by the cooperation of geologists the world over. This is not a theory derived *a priori,* but a discovery painfully and tediously worked out by the systematic study of the faunas of rock formations carefully located in the geologic column. It is an important natural law that *fossil faunas*

and floras succeed one another in a definite and determinable order.

Correlation of the Fragments of the Record. The matching of strata or formations from outcrop to outcrop (or from well to well underground) to determine their mutual relations and degree of equivalence in age is known as *correlation.* It is an important step in working out the geologic history, because no single area contains a record of all geologic time, and if it did the section would be so thick that its base would be buried beyond our reach. It is fortunate, therefore, that the areas of deposition have shifted from time to time in keeping with the irregular warping of the Earth's crust. Although no section is complete, deposition has been constantly going on in one place or another, and we need only discover and correlate enough of the scattered fragments to build up a composite record of all geologic time.

For more than a hundred years the geologists of all countries have been co-operating in this endeavor, and the total thickness of the stratified rocks now recognized would exceed 500,000 feet (= 95 miles) if all the beds were directly superposed.

Some of the criteria used in correlation are illustrated by Fig. 5. The left block (*A*) represents the formations exposed near the mouth of the Grand Canyon, and the right one (*B*) a corresponding section at Bright Angel Trail about 100 miles farther east. A general view of these formations may be seen in Figs. 52 and 150.

At Bright Angel Trail ten formations of stratified rock are recognized, and in the western section there are also ten. When we attempt to correlate one with the other, it appears that No. 10 at Bright Angel Trail is the same as No. 10 at the mouth of the canyon, because (1) it holds the same relative position at the rim of the canyon; (2) it presents the same lithologic appearance (being a buff-weathering, cherty limestone); (3) it agrees in thickness; and (4) it yields the same kinds of marine fossils which in each section are limited to this unit. If more proof were needed, (5) we could follow the rim of the canyon and trace the formation from one section into the other. This is the Kaibab limestone that rims the Grand Canyon from end to end.

In the same way, No. 5 of the eastern section can be correlated with No. 5 of the west. It is the cliff-forming Redwall limestone which maintains the same lithologic character and approximately the same thickness for a distance of more than 100 miles (Fig. 150). Furthermore, it has distinctive fossils, and it crops out in a bold cliff and forms a bench that can be followed continuously along the canyon wall.

This gives us two tie-points or *key horizons* for correlating the distant sections. The intervening formations, however, present more difficulty. In the eastern section No. 6 is a bright red sandstone and

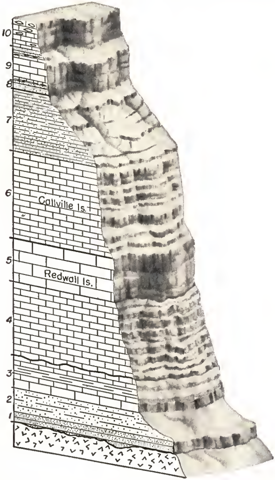


FIG. 5A. Block and section of the formations exposed near the mouth of the Grand Canyon of the Colorado. Recognized formations are numbered 1 to 10.

sandy siltstone with fossil plants and footprints of land animals; No. 6 of the western section is a light gray limestone bearing marine fossils. The two seem to hold the same relative position in the sections, just above the Redwall limestone, but they are totally different in lithology and are unequal in thickness; furthermore, they have no fossils in

common, the one bearing only marine shells and the other only remains of land life. It is evident that both are limited in age to some part of the time between the deposition of the Redwall and the Kaibab limestones, but several alternative relations must be considered: (1) the Callville limestone may be the older, thinning eastward to disappear short of Bright Angel Trail, either because (*a*) it was never de-

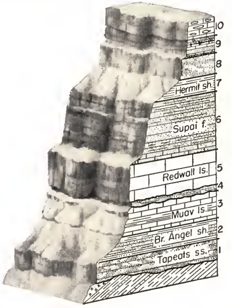


Fig. 5*B*. Block of the canyon wall and section of the formations exposed near Bright Angel Trail, Grand Canyon of the Colorado. Recognized formations are numbered 1 to 10.

posited there, or (*b*) it was eroded away before deposition of the Supai formation; or (2) the Supai formation may be the older, thinning westward for either of the reasons suggested above; or (3) they may be equivalent in age, having formed under different environments; or (4) they may be equivalent in part, with one representing more time than the other. Most of the criteria used to correlate the Kaibab or the Redwall limestone cannot be applied here, for the Callville and Supai formations are dissimilar in lithology, are unequal in thickness, and have no fossils in common. But the Callville can be traced eastward along the walls of the Grand Canyon, and the upper part of it is found to change laterally, as the limestone beds first become sandy, then reddish, and finally alternate with layers of red siltstone and sandstone

(Fig. 187). It *intertongues,* in short, with the Supai formation, and therefore must have been formed at the same time. The intertonguing of these formations, one marine and the other nonmarine, indicates that the seashore fluctuated back and forth across a wide belt during deposition. Fossils, however, indicate that the lower part of the Callville limestone is older than any part of the Supai; hence this part of the Callville formation probably never extended as far east as Bright Angel Trail. More field work actually is needed to confirm this belief.

Still another basis for correlating the Callville limestone and the Supai redbeds might have been used, even if the Grand Canyon had not revealed the lateral gradation and intertonguing of one into the other. The fossil plants of the Supai might indicate the same position in the geologic column as the marine fossils of the upper part of the Callville. This would be true if in some other region—say, New Mexico or Kansas—there were an alternation of marine and nonmarine beds carrying the Supai flora and the Callville fauna. Indeed, correlation of two sections in this manner through a third is common practice.

Similar problems are presented by formation No. 4, which, although it holds the same relative position in each section, between the Muav and the Redwall limestones, differs in lithology and thickness and in faunal content in the two sections.

To recapitulate, it may be noted that formations in separate outcrops may be correlated because of (1) lithologic similarity, (2) similar thickness, (3) similar position in a sequence of formations some of which are known to be equivalent, (4) continuous tracing between outcrops, (5) lateral gradation and intertonguing of one into the other when the formations are lithologically dissimilar, (6) identical faunas, or (7) fossils that are dissimilar (for example, marine versus nonmarine) but are known to occur together elsewhere and therefore to indicate the same age. These are some, but not all, of the means by which strata of the same age are correlated from place to place. Commonly not all of them can be applied to a given situation, but the more that can be used, the more secure the correlation.

Subdivision of the Record

Although time flows continuously, both human and geologic history are punctuated by important events that justify the recognition of distinct ages. Indeed, if we are to describe and discuss the vast record embraced in 500,000 feet of strata, it must be subdivided into con-

venient units, both large and small; and it is highly desirable that the subdivisions should have a natural basis, applicable the world over, so that work in different countries will fit into a common framework. Thus far the attempt has been only partially successful, and we must now examine the problem and its difficulties.

Diastrophism. Those who believe there is a natural basis for subdividing the geologic record—one that is widely applicable—reason as follows (Fig. 6):

1. If deposition of sediment should cease everywhere for a time, a natural break or *hiatus* in the stratigraphic record would result. Even if the sites of deposition merely shifted to inaccessible places—

FIG. 6. Diagrammatic profile across a deep sea basin and parts of two continents; vertical scale greatly exaggerated. Line *a* represents sea level, line *b* the level of the edge of the continental shelf, and line *c* the level of the average depth of the ocean floor.

for example, the floor of the deep sea—the result would, in effect, be the same, since we are directly concerned only with the record that is available on the land areas.

2. At long intervals the Earth's crust has undergone major disturbances that caused mountains to form locally and at the same time produced broad uplift of the continents and deepening of the ocean basins.

3. The margins of the continents drop off rapidly to deep sea which has a minimum depth of 6000 feet and an average of more than 12,000; and the oceans, at present, are slightly more than brimful, spilling over the continental shelves to form shallow *marginal seas* and, in places, spreading farther inland to form shallow *epeiric seas,* like the Baltic (Gr. *epeiros,* the mainland). *Recoverable* sedimentary deposits accumulate only in such shallow seas or on the lands; those of the deep sea are forever lost.

4. Now, if major episodes of crustal disturbance deepen the deep-sea basins, they tend to draw off the water from the shallow seas and to leave the continents exposed to widespread erosion.

5. After such a period of crustal unrest and adjustment, relative stability is attained. Then sealevel rises slowly as each unit of sediment transported to sea displaces an equal volume of water (other factors also may produce a slow rise in sealevel), and the result is

that shallow seas spread again and thus begin a new chapter in the sedimentary record.

6. Inasmuch as the oceans are freely connected, a rise or fall of sealevel is world wide, and major breaks in the record due to deepening of the ocean basins should correspond in all quarters of the globe. Insofar as this is true, we have a basis for subdivision of the record that is both *natural* and *universal.*

Confusing Effects of Local Warping. Thus far we have assumed that the continental masses are stable during the rise or fall of sealevel. Of course, they are not. There is abundant evidence in modern coastal belts that some regions are rising while others are subsiding, and it is quite certain that similar local warping has characterized the movements of the past. Thus, even at times of general continental emergence, some areas are downwarped enough to persist as basins of deposition and even to retain marine waters. In such regions deposition continues even while most of the continent is undergoing erosion. Moreover, local disturbances, even with strong orogeny, may occur during times of general continental submergence, and in such areas there is a conspicuous unconformity and a marked hiatus of relatively local extent. Such irregularity of movement in the land masses makes it difficult to evaluate the breaks in the record and has led to many controversies.

The problem is illustrated diagrammatically by Fig. 7, the upper part of which represents a vertical section across a region of continental dimensions including two geosynclines (at *B* and *D*). In the lower part, twenty horizontal bands are laid off to represent as many units of geologic time, and that part of the stratigraphic record belonging to each time unit is lifted to its proper band, leaving hiatuses (*unshaded*) wherever there is no record. It is now evident that deposition has been nearly continuous in both geosynclinal areas but much interrupted elsewhere.

Certain time units (namely, 3–4, 11–12, and 17–18) have been marked by very widespread submergence and the deposition of a far-reaching marine record; but other units (for example, 7–8 and 14–15) correspond to general emergences and are marked by major hiatuses. Completeness of the record varies almost constantly along the line of section, and yet from this general view it is evident that the strata fall naturally into three major units, I, II, and III. Nevertheless, a local worker, knowing only a small area (such as at *A*, *B*, or *D*), might not recognize this natural subdivision. Workers at localities *B* and *D*, for example, would recognize only two units and would disagree as

to the precise position of the break, whereas a worker at *A* would tend to recognize more than three major breaks. But certainly any number of students who had surveyed the whole record as it is represented in this diagram would recognize three major subdivisions and would agree approximately upon the location of their boundaries.

Still, there is basis for a controversy as to the exact position of the boundary between units III and II, for it falls in time unit 7 at locality

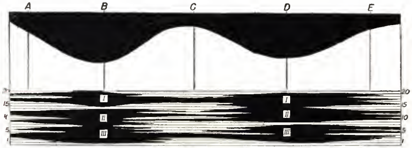


FIG. 7. Diagram to illustrate the nature of the major subdivisions of the stratigraphic record.

The upper figure is a section across a region of continental dimensions, including two geosynclines, the sedimentary rocks being shown in black. The vertical scale is greatly exaggerated.

In the lower figure the horizontal bands represent 20 equal units of time, and the deposits belonging to each are lifted to their proper position. Thus, at each locality along the line of section (e. g., *A*, *B*, *C*, etc.) all units of time represented by deposits appear black, and the times not represented are blank. Thus it is evident that breaks in deposition are few and of short duration in the geosynclines and that they increase in number and importance away from these basins. Furthermore, it is possible to recognize three major units (I, II, and III), even though top and bottom limits of the deposits belonging to each vary in age from place to place and even though the major breaks do not fall precisely at the same time in the two geosynclines.

B, and in unit 8 at locality *D*. The discrepancy may mean that local downwarping kept the sea at *D* after it had disappeared elsewhere, or that local upwarping at *B* caused it to disappear early. Controversies of exactly this sort have arisen concerning the boundaries between most of the systems, and, to some geologists, have seemed convincing evidence that there is no natural basis for subdivision of the stratigraphic record. To others, the confusing effects of local warping only make the task difficult and indicate that revisions may be needed as our knowledge increases.

Biologic Change. Since life is constantly evolving, the species and genera of animals and plants change from age to age. The succession of faunas and floras preserved as fossils therefore provides us with a basis for *chronology;* although if the record were complete, we should

probably have gradual transition and no basis for a natural *subdivision* of the record.

The progress of evolution has been greatly influenced, however, by physical changes on the Earth. Uplift and continental emergence have radically altered the general environment, changing the course of ocean currents, interfering with atmospheric circulation, and producing climatic changes. Moreover, the restriction of the shallow seas to the continental margins has always produced great crowding and keen competition among marine animals that live in the shelf seas. Great crustal disturbances thus bring on critical conditions for most plants and animals and lead to a period of accelerated evolution and many extinctions. These changes take place at the time when epeiric seas have largely withdrawn from the continents and the record is being lost in the deep sea. The subsequent return of marine waters over the lands brings a greatly changed assemblage of animals and plants. Hence *the great physical breaks correspond with major breaks in the biologic record.*

As implied in the foregoing discussion, the geologic column is based largely on the record of marine sediments, chiefly because this record is the more nearly complete and because marine strata are much more widely distributed than nonmarine.

Grouping and Naming of Units

Natural breaks in the stratigraphic record, some great, others small, afford a basis for separating units of rock and corresponding divisions of geologic time.

Eras of Time. Greatest of all breaks were caused by crustal disturbances so profound that they are called *revolutions.* During the last few million years, the Earth has passed through such a time of unrest. It saw the uplift of the great mountain systems of the world —the Alps, the Himalayas, the Andes, the Sierra Nevada, and others— and was accompanied by widespread volcanic activity and by extensive uplift of all the continents. Its full effect will not be realized until the present erosion cycle is completed, and the lands are again worn low and the uplifted sedimentary rocks are in large part eroded away.

Four similar but older revolutions have been recognized, and they separate five *eras* of geologic history, the *Archeozoic, Proterozoic, Paleozoic, Mesozoic,* and *Cenozoic.* These major time units have been named to suggest the characteristic stage of the development of

life by which they are recognized. Thus the Archeozoic is considered the era of most primitive life (Gr. *archaios*, first, + *zoe*, life), and the Cenozoic, of modern types (Gr. *kainos*, recent, + *zoe*, life).

No term is in common use to embrace all the rocks of an era. One speaks simply of the Paleozoic rocks, the Paleozoic record, etc.

The beginning of the Paleozoic era is in some way a date of reckoning of the first importance in geologic history. Records of life are extremely rare and obscure in all older rocks, but are generally abundant in younger ones. For this reason the time preceding the beginning of the Paleozoic era has been called the *Cryptozoic eon* (Gr. *kryptos*, hidden, + *zoon*, animal life), and all later time the *Phanerozoic eon* (Gr. *phaneros*, visible or manifest, + *zoon*, animal life).

Periods of Time and Systems of Rocks. Eras are divided into *periods* of time by relatively great episodes of crustal movement called *disturbances;* and the rocks formed during a period constitute a *system.* A system is commonly named for a region in which it was first comprehensively studied or in which it is particularly well developed, and the corresponding period of time bears the same name. Thus the *Cambrian system* was named for *Cambria,* the Roman name for Wales, though it includes rocks of all parts of the world that were formed during the *Cambrian period* of time. The Devonian system, likewise, was named for Devonshire, England, and includes all the rocks formed during the Devonian period.

Epochs of Time and Series of Rocks. Lesser and more local breaks subdivide the systems into *series* of rock and the periods into corresponding *epochs* of time. Some of the systems are subdivided into two, others into three, four, or five series. These are commonly given geographic names. For example, the Ordovician system in North America is divided into *Canadian, Champlainian,* and *Cincinnatian* series. The last was named for fine exposures about Cincinnati, Ohio, but includes all rocks of equivalent age wherever they can be identified, that is, all rocks formed during the Cincinnatian epoch.

It is commonly not feasible to identify these minor subdivisions in widely separated regions, so a distinct set of series and epochs is recognized in each isolated continent.

Geographic names are generally used for the series and epochs but in systems in which three series are recognized, these are commonly referred to merely as *Lower, Middle,* and *Upper,* without the use of a geographic name. The corresponding epochs are then *Early, Middle,* and *Late.* These words are capitalized when used in this

technical sense for a definite stratigraphic or time unit, but are not capitalized when used in a more general or indefinite sense. Thus, the *Lower Cambrian* rocks were formed during *Early Cambrian* time, but cephalopods first appeared in *late Cambrian* time.

Ages of Time and Stages of Rocks. The rocks of a series may commonly be further subdivided into units called stages. A *stage* may include diverse types of lithology but is characterized by a distinctive assemblage of fossils. It is thus defined on a faunal rather than a diastrophic basis. The corresponding time unit is an *age.*

For examples of the use of stages see Tables 8 to 10 of Appendix B, pages 549 to 554.

Formations. The fundamental stratigraphic unit used in mapping and description is the *formation.* It is a *lithologic unit* (for example, limestone, dolomite, sandstone, siltstone, or shale, or an intimate interbedding of different lithologic types) that can be distinguished at sight from underlying and overlying masses of strata. Several typical formations are shown in the walls of the Grand Canyon (Fig. 5).

The formation is named for a locality where it is first defined and is typically displayed. The *St. Louis limestone,* for example, was named at St. Louis, Missouri, and the *Kaibab limestone* in the Kaibab Plateau of Ariz. When the formation consists of a single kind of rock, the lithology is indicated in the name, for example, *Dakota sandstone* and *Bighorn dolomite;* but if it consists of interbedded types, the lithology can not be thus simply expressed and it is merely designated a formation, for example, *Supai formation* (which consists of interbedded sandstone, siltstone, and shale). The place name is merely a qualifying adjective indicating *which* limestone or sandstone or formation is meant, and it must not be used alone. Thus one writes, "The *Redwall limestone* forms bold cliffs," not "The *Redwall* forms bold cliffs."

A formation may vary considerably in age from place to place. Illustrations may be seen in Fig. 234 on page 370. Here it is evident that deposition of the Selma chalk began in western Alabama while the Coffee sand was forming farther west, but deposition of chalk gradually spread westward. Still later the McNairy sand and the Ripley shale spread farther and farther eastward, restricting the area of chalk deposition. As a result, the top (and the base) of each of these formations varies in age along the Gulf Coast. This is not an exceptional circumstance, but a very normal relation. Since a formation thus commonly varies in age from place to place, it is not feasible to recognize a corresponding time unit.

Groups of Formations. Two or more formations sharing some distinctive lithologic peculiarity may be embraced in a *group*. A good example is the *Glen Canyon group* of massive, cliff-forming sandstones in the Colorado Plateau. Another is the *Newark group* of redbeds that occupy the fault troughs of Triassic date in the Appalachian region. Inasmuch as a group is based upon lithologic peculiarities, it is essentially a local unit, and its upper and lower limits may vary in age from place to place. For these reasons the group, like the formation, has no corresponding time unit.

The Geologic Time Chart

It is essential in all historical studies to discover the order in which events have succeeded one another, for this permits an analysis of cause and effect. Moreover, such a general chronology serves as a framework about which historical data can be organized. The history of the Earth has thus been epitomized in a chronologic scheme known as the *geologic time chart*. It is presented at this place (Fig. 8) because a knowledge of the sequence it records is indispensable in the study of the following chapters. The time units must be thoroughly memorized before we proceed.

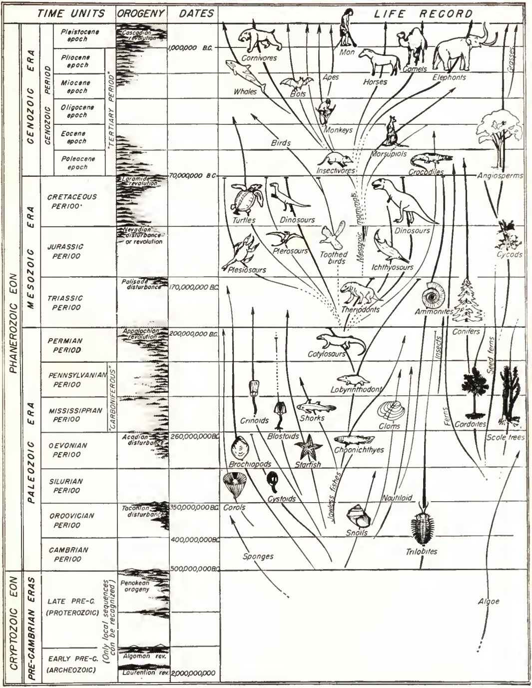


FIG. 8. Geologic Time Chart. Ascending lines indicate the range in time of most of the chief groups of animals and plants. If the line ends in a crossbar, this denotes the time of extinction; if it ends in a dart, the group is still living.

Chapter 2

THE SCALE OF TIME

Philosophers have speculated upon the age of the world since time immemorial, and their beliefs have ranged from that of the Brahmins of India, who regarded the Earth as eternal, to that of Archbishop Ussher of Ireland, who in 1654 deduced from his study of the Scriptures that the Creation had taken place on the twenty-sixth of October, in the year 4004 B.C., at nine o'clock in the morning! Unfortunately this very specific date was inserted by some unknown authority as a marginal reference in the King James version of the Bible, and thus became implanted in religious creed. For a century or more thereafter it was heresy in the Christian world to assume more than 6000 years for the formation of the Earth and all its features, and, as the science of geology grew up under this influence, supernatural explanations were at first invoked to account for many natural phenomena. The unconsolidated sediments and glacial drift spread so widely over Europe were attributed to the Biblical Flood; deep river valleys were believed to be clefts in the rocks formed by earthquakes; and mountain ranges were supposed to have arisen with tumultuous violence. To the uprooting of such fantastic beliefs came the Scottish geologist Hutton, whose *Theory of the Earth*, presented in 1785, marked a turning point in geologic thought on this subject. Hutton argued that the *present is the key to the past* and that, given sufficient *time*, the processes now at work could have produced all the geologic features of the globe. This philosophy, which came to be known as the doctrine of *uniformitarianism*, is now universally accepted. It demands an immensity of geologic time.

The growth of the physical sciences after the Renaissance provided means for a really scientific attack on the problem, and a number of ways of estimating the age of the Earth are now known. Most of them involve uncertain factors that leave the results with a qualitative rather than a quantitative value, but all of them indicate great antiquity. The present belief of geologists (in which astronomers and physicists concur) is that the beginning of geologic time goes back more than 2,000,000,000 years. Three of the most widely used methods

of estimating the length of geologic time are briefly sketched in the following paragraphs.

The Hourglass of the Ages

The sediments carried to the sea by streams accumulate there, like the sand trickling through an hourglass. The possibility of using the rate of accumulation as a measure of geologic time was foreseen by

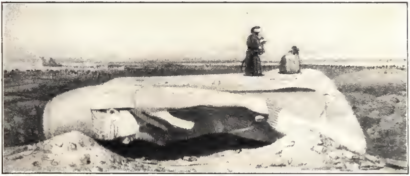


Fig. 9. Colossal statue of Rameses II at Memphis. This illustration by Bonomi in 1847 shows the statue as it lay face down, having fallen from its buried pedestal. About five years later, excavations were made to discover the thickness of the river-laid sediments about its base. The Pyramids of Gizeh are seen in the distance at the left, and the Nile River is near the horizon at the right. Two observers, one standing and the other sitting, indicate the size of the statue.

the Greek historian Herodotus about 450 B.C., when he observed the annual overflow of the Nile spreading a layer of sediment over its valley. He realized that the delta had grown through such annual increments of river-borne muds, and concluded that its building must have required many thousands of years. Confirmation was made in 1854, when the foundation of the colossal statue of Rameses II at Memphis (Fig. 9) was discovered beneath 9 feet of river-laid deposits. Since the statue is known to be about 3200 years old, the rate of deposition at this place has averaged about 3½ inches per century. Furthermore, at Memphis, burnt brick was found in a layer some 40 feet below the surface, and if the rate of deposition has been uniform, this layer must have been deposited about 13,500 years ago. This, moreover, is merely the surface veneer of the delta.

There are other local deposits for which the rate of deposition can be determined, such as the postglacial varved clays in which summer and winter layers, like the growth rings in trees, are seasonal addi-

tions. (See, further, Chap. 18.) Some of the older sedimentary formations appear likewise to be seasonally layered, and if so, the time involved in their deposition can be determined directly. On this basis, 2600 feet of laminated shale in the Green River lake deposits of Colorado and Wyoming is estimated to have required 6,500,000 years to accumulate.[1]

For most of the sedimentary rocks, however, no precise rate of deposition can be determined. However, by setting stream gages at the mouths of the major rivers we can determine the amount of sediment they now bear annually to the sea; and such data for a few of the large rivers permit a rough estimate of the amount supplied by all the streams of the world. If we assume this to be the average rate of erosion for all geologic time, we need only divide the weight of all the sedimentary rocks by the weight of the annual increment to determine the length of time since erosion began on the Earth. But this solution is far too simple. The total mass of sedimentary rock can not be determined with any degree of accuracy because the thickness of such deposits is unknown over large areas, and because a large but uncertain part lies beneath the sea. Moreover, much of the sediment is at present derived from sedimentary rock and is returning to the sea for a second, a third, or perhaps a twentieth time. Probably much of the sedimentary material has been eroded and deposited again and again. Furthermore, we have no assurance that the present rate of erosion is an average one for geologic time; there is good reason to believe that it is far too high, since the lands were raised to exceptional height in late geologic time. It is evident, therefore, that a study of the rate of formation of sedimentary rocks can give us no reliable figure for the total length of geologic time; it merely indicates that the Earth is very ancient.

Sodium in the Sea

In weathering, the sodium of igneous rock is released to form highly soluble salts (notably sodium chloride) that are leached from the soil and carried to the sea. Eventually the water returns as vapor to the clouds, leaving the sodium and chlorine behind. (Some of the chlorine combines with other substances and is deposited, but the sodium remains in solution.) Since seawater is not nearly saturated with respect to sodium chloride, no salt is precipitated (except in landlocked lagoons), and it has steadily accumulated in the sea throughout geologic time.

If all the salt in the sea has been derived in this way, it should serve as a basis for estimating the length of geologic time according to the formula $S/s = A$, in which S is the total mass of sodium in the sea, s is the average increment added in a year by streams, and A is the age of the Earth.

The total amount of sodium now held in solution in the sea can be determined with a probable error of only a few per cent, since the volume of seawater is approximately known and its salinity is almost uniform. The amount of such dissolved salt is staggering; if precipitated in the form of rock salt it would exceed 4,500,000 cubic miles. The sodium alone would weigh 16,000,000,000,000,000 tons.[2]

The annual increment added by streams can also be estimated from data gathered at stream gages at the mouths of representative great rivers, where the flow is recorded from day to day and samples are analyzed for salinity. In this way the salt derived from representative large drainage areas is measured, and the total for all the lands can be estimated. The sodium thus measured is about 158,000,000 tons per year.

If now we substitute the figures quoted, our formula reads

$$\frac{16{,}000{,}000{,}000{,}000{,}000}{158{,}000{,}000} = 101{,}265{,}000 + \text{ years} = \text{Age of Earth}$$

For some years after this calculation was first applied in 1899, the round figure of 100,000,000 years was commonly accepted as the probable age of the Earth; but a little consideration clearly indicates that drastic revisions must be made on several counts.

In the first place, much of the salt currently carried to the sea is not derived directly from the weathering of igneous rocks. Some of it is blown as dust from desert basins or as spray from the oceans; about 14,000,000 tons is mined and used by man and thus artificially liberated into the streams; and much of it is leached from sedimentary rocks where it has been stored in the form of salt beds or of salt water. All of this represents salt previously taken from the sea and now being returned. Such "cyclic" salt makes no permanent addition to the salinity of the seas. In short, the salt now derived anew, by the weathering of igneous rock, is far less than 158,000,000 tons a year. Unfortunately we have no adequate data for making the proper corrections.

Adjustments of another sort must also be made. We have assumed that the present rate of erosion is the average for all geologic time; but

this rate certainly is abnormally high, since we have recently passed through a great period of mountain making and the continents are now almost completely emergent and large areas are undergoing rapid erosion. On the contrary, there were long periods in the past when the continents were low and partially submerged, so that erosion was relatively slight. We have no means of determining the average rate of erosion, but it probably was only a fraction of the present one.

The corrections for cyclic salts, and for the average rate of erosion, would both tend to reduce the average annual increment of salt added to the sea, and this, in turn, would increase the estimated age of the Earth. Since so many uncertain factors are involved, this method at present offers no promise of a reliable quantitative value.

The Radioactive Clock

An electric clock is motivated by the regular oscillation of an alternating electric current, and so it keeps faithful time without winding or care, so long as a steady flow of current is maintained. Still more remarkable are the radioactive elements buried in the rocks that motivate an automatic timepiece for the ages.

Chief of these are the elements *uranium* and *thorium,* the atoms of which are very large and slightly unstable. From time to time each atom discharges a part of its substance as an atom of helium gas accompanied by radiant energy. This loss transforms the parent substance (for example, uranium) into a new element. The atom of this new substance, in turn, looses an atom of helium and more energy, and changes into a third element. This continues through several generations until a stable atom is attained, which proves to be lead. Radium was the first of the intermediate substances in this series to be discovered; it was detected because of its mysterious radiant energy. This peculiarity suggested the now familiar words *radium* and *radioactivity.*

In the cooling of a magma, the uranium (or thorium) unites with certain other elements to form one of several compounds (for example, *uraninite,* a complex uranium oxide, or *ellsworthite*) which crystallize out like other minerals (Fig. 10). After the crystal has formed, the uranium slowly wastes away, and helium and lead accumulate. In so far as these two elements do not escape from the crystal, they form a record of the amount of uranium (or thorium) that has been transformed.

Fortunately the rate of disintegration is very slow and is absolutely uniform under all known conditions of temperature, pressure, or chemical environment; and, also fortunately, this rate can be determined with very great precision by counting the helium atoms emitted within a given time by a measured quantity of uranium (or thorium). They may be recorded automatically by a sensitive electrical device or may be counted directly by observation. For example, if a small quantity of uranium is placed on a screen of zinc sulphide, each escaping atom of helium makes a flash as it strikes the sulphide, and under a microscope these can be seen like fireflies on a dark night and can be counted. Such counts indicate that 1 gram of uranium yields annually 1/7,600,000,000 of a gram of lead.[3] At this rate U grams will produce $1 \times U \div 7{,}600{,}000{,}000$ grams of lead in 1 year, and in t years they will produce $t \times 1 \times U \div 7{,}600{,}000{,}000$. Hence the amount of lead (Pb) produced by a given quantity of uranium (U) in a given number of years (t) may be expressed thus:

$$Pb = \frac{tU}{7{,}600{,}000{,}000}$$

Then, multiplying by 7,600,000,000 and dividing by U, we have

$$\frac{Pb \times 7{,}600{,}000{,}000}{U} = t$$

or

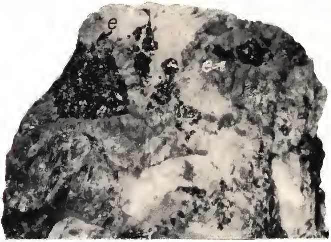
$$t = \frac{Pb}{U} \times 7{,}600{,}000{,}000$$

Therefore, when the lead-uranium ratio, Pb/U, has been determined for a crystal of a uranium-bearing mineral, we can solve the equation for t, the length of time (in years) since the crystal formed. For example, in crystals of uraninite that occur in pegmatites at Branchville, Connecticut, the ratio of lead to uranium (plus thorium) is 0.050, whence $t = 0.050 \times 7{,}600{,}000{,}000 = 380{,}000{,}000$ years.* In precise calculations, allowance is made for the gradual decrease in the quantity of uranium, for the presence of different isotopes of uranium, for the presence of thorium, and for other factors, but the principle is illustrated by the example used above.

In practice it is necessary to find an occurrence of nonweathered uranium-bearing minerals, select a single fresh crystal for analysis,

* Refinements reduce the probable age to about 370,000,000 years.[4]

and determine the ratio of lead to the uranium present. Care must be taken to reject weathered specimens because lead may be dissolved by subsurface water and either carried away or precipitated in the openings in the rocks through which it passes. If part of the



Adolph Knopf.

FIG. 10. A piece of uranium ore from Hybla, Ontario. The light-colored crystals are feldspar and quartz, and the dark (*e*) is *ellsworthite*, a mineral containing 15 to 18 per cent of uranium.

accumulated lead has been removed by solution, the lead-uranium ratio and the calculated age will be too small; but if extra lead has been added from other sources, the ratio will be too great and the inferred age excessive. Fortunately, the atomic weight of the lead derived from uranium is slightly different from that of ordinary lead, and so by very critical checking it is possible to detect contamination.

With very rare exceptions, crystals of uranium and thorium minerals have formed only in igneous rocks, and pure crystals large enough for satisfactory study occur chiefly in pegmatite dikes and other coarsely crystalline plutonic rocks. Therefore, radioactivity permits us to date certain igneous rocks precisely in years, but the age of sedimentary formations must generally be inferred from their associations with dated igneous rocks. Figure 11 illustrates the problem. Assuming that uranium-bearing minerals have been found in the dike at X and that the lead-uranium ratio indicates an age of 60,000,000 years, we know that this is the length of time since the igneous intrusion. But the question remains, What geologic period does this represent? The dike is clearly younger than formation K which it intrudes, but is

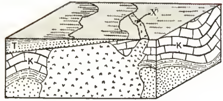


FIG. 11. Block diagram to illustrate the problem of determining the *geologic* date of formation of a radioactive mineral.

older than formation T which unconformably overlaps it. If formations K and T bear fossils by which they can be located in the geologic time scale, we have an absolute geologic date somewhere within this time interval. If this interval is great—for example, Mid-Cretaceous to Mid-Cenozoic—the igneous rock can not be more closely dated, but if the interval is small, as between Late Cretaceous and Paleocene, we have a fixed point in time near the end of the Cretaceous period.

In some cases, however, the pegmatite dikes occur in schistose rocks that can not be directly dated. For example, the pegmatite at Branchville, Connecticut, has yielded uraninite crystals with a lead-uranium ratio indicating an age of 370,000,000 years; but it is in a belt of deformed schists far from any fossiliferous rocks that could determine the geologic period of its intrusion.

The oldest rock thus far determined is in the Pre-Cambrian complex on Winnipeg River in Manitoba. Its lead-uranium ratio indicates an age of 2,300,000,000 years. Pegmatite dikes in the core of the Black Hills at Keystone, South Dakota, record an age of 1,420,000,000 years. Thus far, only a few of the uranium minerals suitable for analysis are closely dated geologically, but future work will undoubtedly increase the number greatly. The following may be cited as the best-established dates in the geologic time scale:

Geologic Age	Age in Years	Locality
Early Cenozoic	60,000,000	Gilpin County, Colorado
Early Permian	230,000,000	Oslo, Norway
Late Cambrian	400,000,000	Güllhögen, Sweden
Late Pre-Cambrian	620,000,000	Katanga, Belgian Congo
Mid Pre-Cambrian	1,420,000,000	Keystone, South Dakota
Early Pre-Cambrian	1,800,000,000	Carelia, Russia
Early Pre-Cambrian	2,300,000,000	Winnipeg River, Manitoba

From these data it appears probable that the beginning of the Cenozoic era was about 70,000,000 years ago, of the Mesozoic about

200,000,000 years, and of the Paleozoic about 500,000,000 years; and it is clear that the Earth is more than 2,000,000,000 years old. This brings out the striking fact that nearly three-quarters of geologic time had transpired before the Cambrian period, which left us the first adequate record of life (Fig. 12).

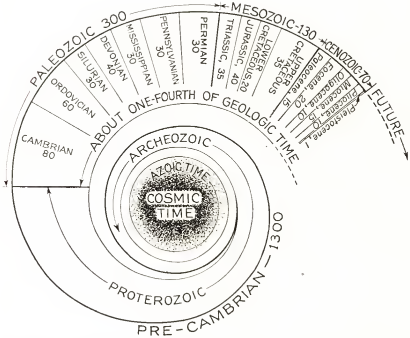


FIG. 12. Geologic time represented as a spiral graph. Numbers indicate millions of years. Modified slightly from David White. Scale for the Cenozoic units modified slightly from data by G. G. Simpson.

"To grasp what these figures mean," Mahony has written, "we may imagine ourselves walking down the avenue of time into the past and covering a thousand years at each pace. The first step takes us back to William the Conqueror, the second to the beginning of the Christian era, the third to Helen of Troy, the fourth to Abraham, and the seventh to the earliest traditional history of Babylon and Egypt; . . . 130 paces takes us to Heidelberg man, and about ¼ mile to the oldest undoubted stone implements of Europe. And should we decide to continue our journey until we meet the most ancient fossil organisms, the journey would exceed 250 miles." [5]

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Chapter 3

FOSSILS, A LIVING RECORD OF THE DEAD

"Race after race resigned their fleeting breath—
The rocks alone their curious annals save."
—T. A. Conrad.

Frozen Carcasses in the Tundra. In August, 1900, a Russian hunter, following a wounded deer along the Beresovka River in eastern Siberia, came upon the carcass of an elephant, partially exposed by recent caving of the river bank. With mingled curiosity and fear he knocked off a tusk, which he later sold to a Cossack. The latter, hearing his story, relayed the news to St. Petersburg that another frozen mammoth had been found. An expedition from the Imperial Academy of Sciences was dispatched as soon as possible and, after a journey of some 3000 miles, reached the locality in September, 1901, after the animal's back had been exposed to the sun of two summers, and wild dogs had gnawed most of the flesh from it. Excavation soon proved, however, that the flesh of the buried limbs and much of the body was still frozen and "red."

The occurrence of this beast 80 miles within the Arctic Circle and more than 2000 miles north of the present range of elephants is no more remarkable than the features of the animal itself. Unlike any living elephant, it bore a heavy coat of yellowish-brown wool interspersed with long black hair. Its head was very short and high-crowned, and its profile quite unlike that of any modern elephant. It was, in short, a specimen of the extinct woolly mammoth, a species that ranged widely over the snowfields of Europe and North America during the last of the Pleistocene ice ages. Unmistakable pictures of these beasts were left by the ancient cave dwellers on the walls of some of the caverns in France (see Fig. 13), but the species has been extinct so long that there are no allusions to it either in historic records or in the legends of any living peoples.

Broken bones, clotted blood in the chest, and unswallowed foliage in the mouth of the Beresovka mammoth clearly indicated a sudden, accidental death. It apparently fell from the bluff above and was soon frozen, to remain in cold storage for perhaps 20,000 years. Parts of

the flesh, clotted blood, and hair are now preserved in the United States National Museum, and the skeleton, with most of the hide and entrails, is on exhibition in the Zoological Museum of the University of Leningrad.

Images in Stone. Less spectacular but no less real are the bones and shells of animals entombed in solid rock in many parts of the world. Whether the skeleton of a dinosaur or a mere broken shell, these are remains of creatures that lived and died and were buried in

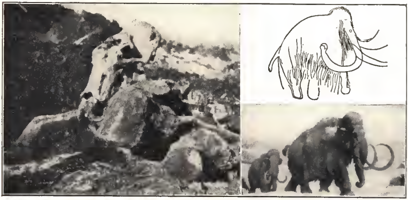


FIG. 13. The woolly mammoth. Left, the Beresovka specimen, a frozen carcass after partial excavation; lower right, a modern restoration of the species, by Charles R. Knight, based on this and other specimens; upper right, a drawing by Paleolithic man on the wall of a cave at Combarelles, France.

sediments that later solidified into stone. The ancients observed such "images in stone" and speculated upon their meaning. The Romans called them *fossils,* because they were objects dug up (Lat. *fossilis,* from *fodere,* to dig), and we have borrowed that name. The study of fossils is the science of *paleontology* (Gr. *palaios,* ancient, + *onta,* existing things, + *logos,* a discourse or science).

Nature of Fossils. The term fossil was at first loosely applied to any curious object found in the rocks, whether organic remains or mineral, but it gradually came to be restricted to the former. As now defined, it includes *any recognizable organic structure, or impression of the same, preserved from prehistoric time.* Ordinary coal and petroleum are not regarded as fossil, in spite of their organic origin, because they show no *recognizable organic structures.* Some coals, however, include fragments of fossil plants with their actual cellular structure preserved.

The remains of an animal or plant recently dead are not considered fossil, even though naturally buried and preserved—a considerable antiquity is implied by the term; but since the present grades insensibly into the past we must either assign an arbitrary boundary or leave a broad indefinite zone back of which organic remains are considered fossils and after which they are not. One geological wag has proposed that "if they stink the remains belong to zoology, but if not, to paleontology." Extinction is not a criterion by which to judge whether an object is a fossil. The majority of fossils do represent extinct species, but there are many kinds of animals and plants that have been in existence since prehistoric time, and ancient remains of these are fossils. On the contrary, some, like the dodo and the passenger pigeon, have been exterminated within the last few centuries, and their remains, if of historic times, are not considered fossils.

Types of Fossilization

Actual Preservation. The preservation of flesh and other soft tissues is a very rare phenomenon, possible only where bacterial action and decay have been almost miraculously inhibited. Oil seeps have, in a few instances, supplied sufficiently antiseptic conditions for the preservation of flesh since Pleistocene time, and the frozen soil of the Arctic has yielded both the woolly mammoth and a long-haired rhinoceros, but no animals older than the latest Pleistocene ice age have been preserved entire.

The Beresovka mammoth (Fig. 13) was one of the most complete frozen fossils ever found, but the skeleton of another equally remarkable carcass was brought back to St. Petersburg from the Lena River delta in 1799, and there are recorded fifty-one Siberian occurrences where parts of the flesh and skin have been preserved. A few similar but fragmentary finds have been made in Alaska.

In the museum at Lemberg, Poland, there stand side by side the skeleton and the mounted skin of a woolly rhinoceros, an extinct species adapted, like its contemporary, the woolly mammoth, to life in the Pleistocene snowfields. This specimen, like several others, with parts of the skin and flesh still adhering to the bones, was found in an oil seep in Galicia. Another remarkably complete specimen was excavated in the district of Sarunia, Poland, in 1930.

Although soft tissues rarely occur fossil, the hard parts, such as bone, shells, or woody tissue, have commonly been preserved since

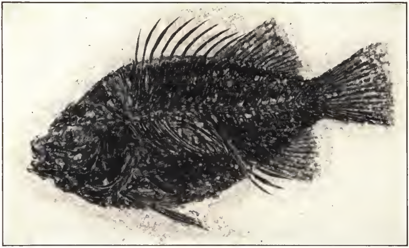

CHICAGO NATURAL HISTORY MUSEUM.

Fig. 14. A skeleton in the rock. This complete skeleton of an extinct ground-sloth (Scelidotherium bravardi) was discovered in the bank of a small arroyo in the Pampas formation in Argentina by the Marshall Field Paleontological Expedition of 1927, and is now shown in the Chicago Museum exactly as it lay in the rock. Length, about 8 feet.

early Cenozoic time with little change. The logs embedded in Eocene lignites of Germany have suffered slight decay and discoloration, but the grain and texture of the wood are still preserved with little chemical alteration. Cenozoic shells embedded in marl or clay likewise show little change. Some of the Upper Cretaceous shells, in spite of their 70 million years or more of antiquity, show scarcely any alteration, retaining faithfully the delicate details of surface sculpture, and rarely even the color pattern.

Petrifaction. In the older rocks, the hard parts alone are usually preserved, and these commonly appear to be turned to stone, as indeed they are. Such fossils are said to be *petrified* (Lat. *petra,* stone, + *facere,* to make). The change from the original condition is accomplished in one of the following ways:

1. *By permineralization.* If the original structure is porous, as a bone or many kinds of shells, mineral matter may be added from the underground water to fill up all the voids without altering the original substances. This makes the object heavier, more compact, and more stonelike, at the same time protecting it from the penetration of air or solutions that would dissolve and destroy it. Such fossils are said to be *permineralized.* Petrified bones are usually of this category (Figs. 14, 15).



Carl O. Dunbar.

FIG. 15. Skeletal remains of a fish preserved in the slabby limestone of the Green River formation (Eocene) in Wyoming. The fossil is permineralized. About ½ natural size.

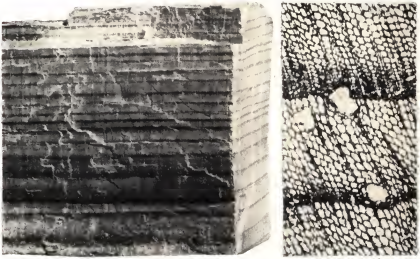


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FIG. 16. Petrified wood from the fossil forests of the Yellowstone National Park. At the left, a piece of the silicified wood about natural size, showing the grain, growth rings, and medullary rays; at the right, a thin section cut from the end of this piece, enlarged about 10 times to show the cells of the wood in parts of 3 growth rings. Photographs not retouched.

2. *By replacement.* The original substance may, however, be dissolved and *replaced* by mineral matter of a different sort. Wood is commonly preserved in this way, the woody tissue being replaced by silica. As a rule, the change is so gradual and so delicate that the cell walls and all the microscopic structures of the wood are preserved, even after the organic matter is gone, and the log is literally turned to stone (Fig. 16). The fossil forests of the Yellowstone provide a striking and familiar illustration. Such replacements by either silica or calcium carbonate are known as far back as the Devonian period.

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FIG. 17. Carbonized fern leaves in a deep well core. Half natural size. Not retouched.

On the other hand, the substitution may result in the loss of all internal structure while preserving the gross form of the organic object, as, for example, a coral or shell replaced by quartz, calcium carbonate, dolomite, etc. Such a fossil is a false replica or *pseudomorph.*

3. *By distillation.* The volatile elements of organic material may be distilled away, leaving a residue of carbon to record the form of the object. Leaves are generally preserved in this way, and the beautiful

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Fig. 18. A fossil ichthyosaur, a marine reptile from the Lower Jurassic shales of Holzmaden, Germany. The skeleton is permineralized; the flesh reduced to a film of carbon. This species ranges from 8 to 10 feet in length.

"carbon copies" of fern leaves and other foliage in the shales above many coals give a vivid picture of the ancient vegetation (Fig. 17). More rarely the presence of animal tissues is recorded in this manner in black shales. A striking example is afforded by the extinct marine reptiles known as ichthyosaurs, whose skeletons found in Lower Jurassic black shales of Germany are in some instances surrounded by a film of carbon preserving the outline of the fleshy body with its fins and tail flukes (see Fig. 18). Even jellyfish and soft-bodied worms are thus preserved in Mid-Cambrian rocks almost 500 million years old (Pl. 3, and p. 147).

Molds, Casts, and Imprints. Shells or other organic structures embedded in rock may later be dissolved by percolating ground water, leaving an open space that preserves the form of the object. This hole is a *natural mold.* By pressing into it some plastic substance like dental wax, we may obtain an artificial *cast* or replica of the original (Fig. 19). Percolating subsurface water has in many instances filled such holes with some other mineral substance, usually quartz, thus producing *natural casts.* The molds of thin objects like leaves are commonly spoken of as *imprints* (Figs. 17, 20). The pattern of the scales in the skin of some dinosaurs is well shown by impressions in the matrix, although no other trace of the skin is preserved (Fig. 245, p. 385). The terminology applied to fossils thus follows that of foundry practice, the *cast* being the replica of the original and its counterpart being the *mold.* Hollow objects may have, besides the external mold, an internal mold or *core.*

The most remarkable of all natural molds are those of the insects preserved in amber (Fig. 21). This substance is merely the hardened resin of ancient conifers. While the resin was fresh and soft, insects and spiders frequently became entangled and embedded in it. Here they were preserved until the resin had hardened. In the millions of years that have since elapsed, the delicate organic tissue has dried almost to nothing, but the dark, lifelike molds in the transparent amber look like the real insects and retain even the microscopic hairs or wing scales. With a microscope it is thus possible to count the filaments on the antennæ of gnatlike species that lived and died more than 25 millions of years ago! If the amber is treated with a solvent, however, almost nothing remains; the insect fossils are but delicate hollow molds. Most of the amber of commerce weathers out of lignite-bearing sediments of Oligocene age along the Baltic coast of eastern Germany.

Footprints and Trails. (See Fig. 22.) The tracks left by a living animal are considered fossils, and they supplement the other remains

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Fig. 19. Left, molds of marine shells on the surface of a chunk of Devonian sandstone; right, a cast made by coating the surface of the rock with liquid latex which, after hardening, was peeled loose and turned over from left to right.

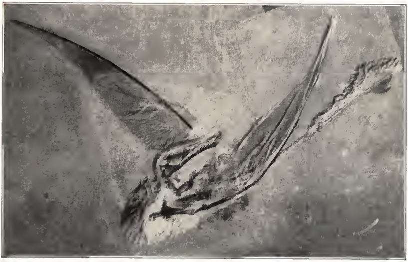

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Fig. 20. A flying reptile (***Rhamphorhynchus phyllurus***), with the delicate wing membrane preserved as an imprint in a fine-grained limestone. Upper Jurassic, Eichstadt, Bavaria. About $\frac{1}{5}$ natural size.

in most interesting ways. For example, the bipedal dinosaurs were shaped much like kangaroos, with powerful hind legs and diminutive fore limbs, yet we know as certainly as if they were still living that they ran like an ostrich instead of leaping like a kangaroo, for their tracks invariably alternate and are never paired. From the tracks we can tell whether an animal was bipedal or quadrupedal, whether its locomotion was by running, leaping, or sprawling, and whether it was agile or ponderous. Tracks alone give us some of the earliest records

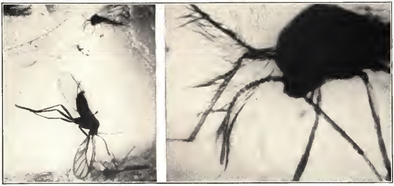

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Fig. 21. Insects preserved in amber. Left, 2 tiny specimens enlarged about 5 times; right, the smaller (upper) specimen enlarged nearly 50 diameters, showing the microscopic filaments on its antennæ. From the Oligocene deposits of the Baltic coast of Germany.

of land vertebrates, and in several formations tracks alone record the presence of animals where no skeletal remains have been preserved.

Coprolites. Fossil excrement constitutes another class of fossils, known as *coprolites*. These often contain the scales of fishes and other hard parts of animals that were devoured. Wherever associated with skeletal remains in such a way that their source can be recognized, coprolites are of special significance for the light they throw on the food and feeding habits of the animal in question. For example, the dried dung found with fossil ground-sloths at two localities, one in South America and the other near El Paso, Texas, gives the only proof we have of the type of vegetation preferred by that race of extinct monsters.

Conditions Favoring Preservation

The buffalo carcasses strewn over the plains in uncounted millions two generations ago have left hardly a present trace. The flesh was

devoured by wolves or vultures within hours or days after death, and even the skeletons have now largely disappeared, the bones dissolving and crumbling into dust under the attack of the weather. This suggests that special conditions are required for the preservation of organisms as fossils. Two such conditions are paramount.

Fig. 22. Tracks of a three-toed dinosaur in a bed of Lower Cretaceous limestone near Glen Rose, Texas.

The Possession of Hard Parts. Although leaves are commonly preserved as imprints or carbonized films, animal flesh decays so rapidly that any form of preservation is rarely possible. It is not surprising, therefore, that many groups of animals, like the jellyfish and worms, have left almost no geologic record. The rare instances where soft-tissued animals are preserved, as in the Mid-Cambrian black shale of Mount Wapta (p. 146), serve only to show what a wealth of animal life existed which ordinarily perished without leaving a trace in the rocks. It is evident that animals with hard parts, either external or internal, have an overwhelming advantage in the chance for preservation.

Immediate Burial. A carcass left exposed after death is almost sure to be torn apart or devoured by scavengers. If it survives these larger enemies, bacteria insure the rapid decay of all but the teeth, bones, and shells. Even these hard parts are soluble and tend to crumble and fall into dust under the attack of the weather. If buried by moist sediment, however, weathering is prevented, oxygen is excluded, and bacterial action is greatly reduced. For these reasons quick burial is perhaps the most important condition favoring fossilization. Natural burial is accomplished in various ways.

Caves provide protection against the weather not only for the living but also for the dead, and they have commonly served as the lairs of wild beasts which dragged in the carcasses of their prey and left the bones scattered over the cavern floor. In other instances, they were connected with sinks in limestone in which unwary animals were trapped. In any case, the bones were protected from weathering and commonly were covered by clay or by calcareous deposits such as the stalagmites that form on cavern floors. Man was a common inhabitant of such caves during the Pleistocene ice ages, and by far the most important discoveries of early human fossils have been made in these abodes. One of these is shown in Fig. 325, p. 502.

In many caverns explorers have come upon amazing concentrations of fossil skeletons. The cave shown in Fig. 23, for example, has yielded 46 species and 41 genera of vertebrate animals, including wolves, bears, mastodons, tapirs, wild horses, deer, and an antelope.

Land animals may be buried by *miring in asphalt deposits, bogs, or quicksand,* any one of which provides a protecting cover.

In the summer of 1939, while four boys were playing near an old gas plant at Mount Pleasant, Michigan, they noticed a glossy area of tar that had been discharged as waste in the manufacture of coke and gas. One of them ventured out upon it but, when partly across, began to stick and found himself slowly sinking. Two companions rushed to his aid, and they, too, were trapped like flies on sticky paper. The fourth lad ran for help, which arrived none too soon, for the first boy, when rescued, was already submerged up to his neck and the others were waist-deep. Submergence to this depth had required somewhat less than half an hour.[1]

This incident vividly illustrates the origin of such fascinating fossil deposits as that of Rancho La Brea near Los Angeles. Here there are extensive deposits of asphalt, formed about natural oil seeps. Throughout the ages the volatile parts of the escaping oil have evaporated, leaving behind the sticky residue of asphaltum, which formed a death trap for the prehistoric animals of southern California. Animals coming to the seeps for water, or attempting to cross soil-covered patches of asphalt, were trapped like the Michigan lads. Their death cries attracted carnivores and scavengers which in turn became engulfed. Their bones still lie beautifully preserved—although all in a jumble—in the asphalt deposits, from which they have been recovered by the hundreds of thousands (Fig. 24).

The bones are marvelously preserved in such deposits because bacteria can not live in asphaltum and decay is inhibited by it. No flesh

has been found at Rancho La Brea, but other oil seeps in Poland have yielded the carcasses of the woolly rhinoceros previously mentioned.

In New England and other eastern states another kind of death trap is recorded in the bogs now largely filled with peat and muck.

J. W. Gidley and C. L. Gazin, U. S. National Museum.

FIG. 23. Limestone cavern intersected by a railroad cut near Cumberland, Maryland. Traces of an ancient opening could be seen at the top of the cliff. The 46 species of vertebrate fossils recovered from this cavern are of Pleistocene age.

These came into existence as open lakes during the closing stages of the last Ice Age some 20,000 years ago, and in the ensuing millennia were gradually filled with moss and other swamp vegetation. In many instances the vegetation formed a floating mat over open water. This proved to be treacherous for some of the heavy animals of the time, notably the mastodon, teeth or skeletons of which have been found in many of the bogs. In New York State alone no fewer than 217 such elephants have been discovered.

One of the most striking of all the bog deposits is that of Big Bone Lick, Kentucky, about 20 miles southwest of Cincinnati, from which more than 100 mastodons have been recovered, along with skeletons of the bison, reindeer, moose, and wild horse. This locality was known to Thomas Jefferson, who, during his presidency, reserved one room in the White House as a museum for his fossils from Big Bone Lick.

Fig. 24. An asphalt trap. Above, restoration of a scene at the Rancho La Brea asphalt pit during Pleistocene time, made by Charles R. Knight for the American Museum of Natural History. Left foreground, a saber-toothed tiger, Smilodon, snarls at a group of giant ground-sloths while vultures wait overhead, and in the distance a herd of imperial elephants is in view. Below, left, a jack rabbit recently trapped in the asphalt; right, a mass of fossil bones in the asphalt deposits. Upper picture from the American Museum of Natural History; lower ones from the Los Angeles Museum.

The "quicksand" in the channels of aggrading streams has also claimed many victims, which appear in the fossil deposits of ancient channel sands. In 1942 a locality was discovered in the Pleistocene beds of San Pedro Valley, California, where mastodons had mired in the marsh about a salt lake; their limb bones still remain upright in the deposit.[2]

Falls of volcanic ash (Fig. 25) commonly kill and bury, as the tragic fate of Pompeii reminds us. Many fine fossil deposits in the Cenozoic rocks of western United States are in volcanic ash, like those of the John Day Basin in Oregon and Lake Florissant in Colorado. Flows of lava sometimes overwhelm timber, charring the tree trunks and then solidifying before actually burning the wood; tuff and volcanic breccia also overwhelm and cover trees. In this way the magnificent fossil forests of the Yellowstone were buried. Figure 26 shows a remarkable instance where fern leaves left an imprint on a thin flow of lava. In this unusual case the leaves were probably green and wet and the

R. F. GRIGGS, NATIONAL GEOGRAPHIC SOCIETY.

Fig. 25. Volcanic ash after the eruption of the Alaskan volcano, Katmai, in 1912. The white line indicates the profile of the mountain before the eruption. In the foreground is timber, killed and largely buried by the ash fall. It is estimated that 5 cubic miles of ash and pumice were ejected during this eruption, and ash that fell as much as 200 miles to the southeast of the volcano made a layer an inch thick.

flow was very thin, so that the lava hardened before the leaves were burned.

In deserts and along the seashore, *wind-blown sands* may overwhelm the living or bury the dead. Dry sands are not a good medium for fossilization, since oxygen can penetrate to great depths and solution

Harold S. Palmer.

FIG. 26. Fern leaves preserved in lava. During an eruption of Kilauea, island of Hawaii, in 1868, these ferns were covered by a thin flow of lava. They were probably green and wet at the time and thus escaped destruction until the lava had solidified.

after rainfalls is very active. Hence fossils are rare in desert deposits. Nevertheless the nests of dinosaur eggs found in Mongolia (Fig. 247) were apparently preserved in this way by drifting sands.

Water-borne sediments are so much more widely distributed than all other agents of burial that they include the great majority of all fossils. Flooded streams drown and bury their victims in the shifting channel sands or in the muds of the valley floor (Fig. 27). Whether these objects are drift logs or leaves or animal bodies, the result is the same; they are buried in low places where the ground is generally

moist, if not permanently water-covered, and where rapidly accumulating sediments give them ever deeper and more permanent burial.

The shallow sea floor is the ultimate repository of most of the sediments, and it is almost everywhere covered with such loose material in or upon which the teeming bottom life dwells. It is the inevitable fate of many shells on the sea floor to become quickly and even suddenly covered with mud or sand during storms. For this reason, *the sea bottom is the greatest region for the preservation of fossils,* and marine formations are rarely unfossiliferous.

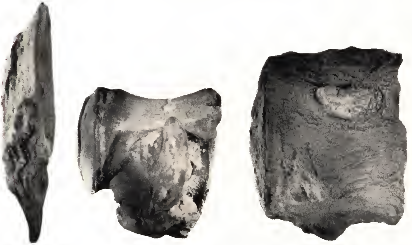
It is hardly necessary to state that fossils never occur in plutonic rocks and are not to be found in any igneous rocks except where ash falls or nearly cooled lavas have overwhelmed plants and animals. They occur in all types of sedimentary rocks but are generally least common in pure sandstones and most abundant in calcareous shales and limestones. Red sandstones and shales usually have few fossils, except footprints, because the red color is due to complete oxidation, and this destroys organic compounds. Even where abundant tracks prove the existence of plentiful life, as in the Triassic redbeds of Connecticut, skeletal remains are rare.

After preservation, fossils may be distorted or completely destroyed during the deformation and recrystallization of rocks involved in strong

E. S. DANA.

Fig. 27. A modern forest killed and in process of being buried by alluvium on the delta of the Yahtse River, Alaska.

folding or thrusting. Even the compaction of some types of sediment, notably black muds, causes shells or bone to be squeezed flat (Fig. 28). The flow of weak rocks during folding commonly distorts fossils into grotesque forms. Metamorphic rocks frequently show blurred



Yale Peabody Museum.

FIG. 28. Fossils deformed by settling and compaction of enclosing sediments. Three vertebræ of a marine reptile (*Mosasaurus*) from Cretaceous (Niobrara) chalk of Kansas. The one in the center is undeformed; that at the left was flattened by pressure against its ends; and that at the right was flattened by pressure against its sides. All were alike when buried. About ½ natural size.

traces of fossils (as in many marbles), but where recrystallization has been complete, all traces of organic remains are destroyed.

INTERPRETATION AND RECONSTRUCTION OF FOSSILS

Early Interpretations. History does not record the first observation of fossils. A Jurassic brachiopod has been found among the amulets of Neandertal man at Saint-Léon (Dordogne), France, and there are other evidences of aboriginal fossil hunters. In the writings of the Greeks, there are occasional references to such objects long before the beginning of the Christian era. It is interesting to note that some of these early observers correctly interpreted the organic remains and drew significant inferences from their presence in the rocks. Herodotus, for example, during his African travels about 450 B.C. observed fossil sea shells in Egypt and the Libyan desert, from which

he correctly inferred that the Mediterranean had once spread much farther to the south than it does today. On the other hand, much fancy and mysticism were associated with fossils even by great thinkers like Aristotle, who, while believing them to be organic, thought they grew in the rocks. His ideas of how this came about were rather obscure, but his pupil, Theophrastus, clearly expressed the interpretation that eggs or seeds buried with accumulating sediment had germinated after burial and grown in the rocks!

The natural interpretation of fossils as organic remains of some sort seems to have been general until the beginning of the Dark Ages, when the Christian church came to insist upon a belief in a special creation accomplished in six days, and a beginning of the Earth at a time only a few thousands of years ago. This belief left no place for extinct creatures or great changes in the position of land and sea. Under this influence, interest in fossils was so subdued that few references to them appear in the literature of the Dark Ages. With the Renaissance, however, and the growth of natural science, fossils again claimed attention and soon became the subject of a controversy that fully equaled in fanaticism and bitterness the modern controversy over Organic Evolution.

The "Fossil Controversy." The controversy really began in Italy about A.D. 1500, when the digging of canals through Cenozoic marine formations brought to attention abundant shells so obviously like those of the present sea coast that their significance could hardly be doubted. Leonardo da Vinci, who besides being an artist was trained as an engineer, took a great interest in these fossils and argued clearly that they were shells of animals once living in the places where they were found. There were many who flatly denied this, and for two centuries the controversy raged, advocates of the Organic Theory being frequently subjected to persecution. The most fantastic explanations were invented to avoid the biologic interpretation of fossils. Some were entirely mystical, attributing them to a "plastic force" at work in the rocks, while a few simply declared them "devices of the Devil," placed in the rocks to delude men. One of the most remarkable illustrations of such fanaticism occurred in Germany as late as 1696, when parts of the skeleton of a mammoth were dug from the Pleistocene deposits near Gotha. These fell into the hands of Ernst Tentzel, a teacher in the local gymnasium, who declared them to be the bones of some prehistoric monster. The aroused public demanded a hearing, and the evidence was examined by the medical faculty of the

school, which issued the official verdict that the objects were but a "freak of nature"!

When at last many devout Christians could no longer doubt the organic nature of fossils, a new idea came to the fore that made this concept not merely acceptable but welcome: all fossils were attributed to the Flood described in the Scriptures. The extreme to which this idea was carried is immortalized in a solemn Latin volume published by Johann Scheuchzer in 1726, entitled *Homo diluvii testis*. It contained the description and figures of articulated skeletons from certain Mid-Cenozoic lake beds at Oeningen, Switzerland (Fig. 29). Although in 1702 he had treated fossils as "sports of nature," Scheuchzer now declared these to be human remains preserved since the Flood. When the great paleontologist, Cuvier, later restudied one of the best of these specimens and found the skeletons to be only the remains of giant salamanders, he referred them to the genus *Andrias* and named the species *scheuchzeri!* Two reptilian vertebræ were likewise described and figured by Scheuchzer as "relics of that accursed race that perished with the Flood," and his figures were published in the "Copper Bible" edition of the Scriptures in 1731.

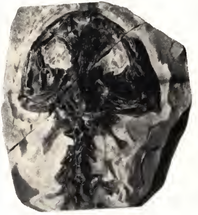


FIG. 29. Skull and part of skeleton of *Homo diluvii testis*, a large salamander from the Oligocene lake beds at Oeningen, Switzerland, mistaken by Johann Scheuchzer for the skeleton of a human being drowned during Noah's flood. About ¼ natural size.

In 1706 a mastodon tooth discovered in a peat bog near Albany, New York, was sent to Governor Dudley of Massachusetts, who under date of July 10 wrote to Cotton Mather about it as follows:

"I suppose all the surgeons in town have seen it, and I am perfectly of the opinion it was a human tooth. I measured it, and as it stood upright it was six inches high lacking one eight, and round 13 inches, lacking one eight, and its weight in the scale was 2 pounds and four ounces, Troy weight.

"I am perfectly of the opinion that the tooth will agree only to a human body, for whom the flood only could prepare a funeral; and without doubt he waded as long as he could keep his head above the

clouds, but must at length be confounded with all other creatures and the new sediment after the flood gave him the depth we now find."

It is difficult to realize that these words concerning a mastodon tooth were written in pious seriousness and not as a jest!

Still another illustration is needed to show that little was known of the significance of fossils before the nineteenth century. The case of Johannes Beringer will suffice. He was a teacher at Würzburg and an ardent collector of fossils who frequently took his students to a soft shale outcrop where fossils weathered out. As a joke some student carved an image of an animal on a bit of the stone and left it for the next trip. When the credulous Beringer found it and accepted it with enthusiasm, the prank was continued until a large collection was assembled, including images of insects, flowers, frogs, and astronomical objects. These were eventually described and figured in 1726 in a volume entitled *Lithographia würceburgensis.* When, shortly afterward, Beringer found Hebrew letters, and even his own name, inscribed on the stones, he realized that he had been the victim of a hoax, and in humiliation he attempted to buy and destroy the entire edition of his book. After spending all he had, he died in poverty and sadness. Ironically adding insult to injury, his family, to recoup their lost fortune, republished the work after his death and sold it as a curiosity.

The controversy over fossils only served to kindle the interest in these objects, and by the beginning of the nineteenth century fossil collecting had become a hobby with many devotees in the church and out, one of the first large collections being made at the Vatican. By the year 1800 the organic nature of fossils was almost universally recognized, and learned men were generally agreed that they represent the life of the geologic past.

Modern Interpretations. *Geographic Significance.* There are many groups of animals that live exclusively in the sea. Corals, brachiopods, crinoids, sea-urchins, and cephalopods are but a few examples. Their occurrence as fossils in a rock implies the presence of a sea at some former time, even though the fossils are now far inland and at great elevations in the mountains, as the Eocene fossils in the Himalayas at 20,000 feet. The coral reefs so common in the Silurian limestones of northern Indiana leave no doubt that a great bay or inland sea like Hudson Bay or the Baltic Sea covered Indiana during Silurian time. If we plot the distribution of Silurian rocks that bear marine fossils, we can determine at least the minimum extent of this ancient seaway. If in other regions we find fossil land plants with stumps or roots in place, or if we find abundant bones

or shells of land animals, it is evident that the enclosing rocks were formed above sealevel. Fossils thus indicate the past distribution of lands and seas.

They may also prove the former existence of land bridges between continents now separated by oceans, or the submergence of present land bridges. For example, the sudden appearance of the "elephants" in North America in Miocene time, long after they had developed in Eurasia, can mean only that America was then connected by a land bridge (Behring) with the Old World. By similar reasoning, it can be shown that at several times in the past North and South America have been separated or united. At present the species of marine animals on the Atlantic side of Panama and Central America are almost all different from those on the Pacific coast, and there is no way for them to mingle without an impossible migration through the cold waters by way of Cape Horn. Therefore, when in certain of the older rock formations we find the same species of fossils in the Gulf region, along the northwest coast of South America, and in California, it is evident that a strait existed somewhere across the isthmus. Here we can get a double check, for when the marine animals were free to cross from the Atlantic to the Pacific side, the land animals in North and South America were isolated and developed independently.

Climatic Implications. Most kinds of animals and plants are now restricted to definite climatic environments. Palms and crocodiles characterize the tropics and subtropics, as the reindeer and musk-ox do the Arctic. The presence of the former as common fossils in the Oligocene rocks of the Dakotas bears a very strong implication that the winters at that time were much milder than now in the Great Plains region. Likewise the presence of fossil musk-ox in Arkansas and of reindeer in France in Pleistocene sediments accords with unmistakable evidence of glacial climates at that time.

In reasoning thus from the known distribution of living types, we are fairly secure for late geologic time but less and less so as we go back to the older rocks where the species and even the genera are different and may have had different habits. Caution must be exercised even for relatively recent geologic time, since animal and plant life are highly adaptive and certain extinct species may have been adjusted to different climatic extremes than living species are. Of course the implication of a *group* of species is more trustworthy than that of one. Cumulative evidence may thus be convincing even for Mesozoic or Paleozoic faunas. For example, since living reptiles and amphibia of every sort become torpid when the temperature drops to near freezing, the

inference is justified that this was true for most, at least, of the great Mesozoic reptiles. Small reptiles and amphibia survive cold weather by crawling into holes or burrowing in the ground where they are protected during their helpless condition, but large species, unable to find such refuge, live only in regions of no frost. There is a strong implication here that dinosaurs and other great reptiles of the Mesozoic could live only in regions of warm temperate to tropical climates.

Documents of Evolution. Since fossils record life from age to age, they show the course life has taken in its gradual development. The facts that the oldest rocks bear only extinct types of relatively small and simple kinds of life, and that more and more complex types appear in successive ages, show that there has been a gradual development or unfolding of life on the Earth. Moreover, series of closely allied species and genera of a single stock, from successive horizons, provide clear instances of gradual evolution. The horse series from the Cenozoic beds of western United States is a classical example, showing in detail the development of the modern horse from a tiny, forest-dwelling ancestor with three toes on each hind foot and four toes on each front foot. Although the comparative study of living animals and plants may give very convincing circumstantial evidence, fossils provide the only historical, documentary evidence that life has evolved from simpler to more and more complex forms.

Dating the Record. Inasmuch as life has evolved gradually, changing from age to age, the rocks of each geologic age bear distinctive types of fossils unlike those of any other age. Conversely, each kind of fossil is an *index* or *guide fossil* to some definite geologic time. For example, trilobites lived only in the Paleozoic era, and the particular trilobite genus *Olenellus* lived only during Early Cambrian time; whereas the horned dinosaur *Triceratops* lived only in the Cretaceous period and three-toed horses only in the middle part of the Cenozoic.

During the last hundred years, paleontologists in many parts of the world have co-operated in gathering such a mass of this kind of information that it is now as easy for a trained specialist to identify the relative geologic age of a fossiliferous rock formation as it is to determine the relative place of a sheet in a manuscript by its pagination. Fossils thus make it possible to recognize rocks of the same age in different parts of the Earth and in this way to correlate events and work out the history of the Earth as a whole. They furnish us with a *chronology*, "on which events are arranged like pearls on a string."

In the previous paragraphs we have assumed as an established fact the gradual evolution of life throughout geologic time. This provides a rational and convincing explanation for the sequence of fossil forms that we find in the rocks. But it is important to realize that *the sequence of fossils was not assumed and does not rest on any theory;* as explained on p. 8, it was discovered by patient exploration and discovery in many regions where there are thick sections of fossiliferous rocks having simple structure, so that the beds are known to be in their normal order of superposition, the oldest at the bottom.

Reconstructions. The majority of fossils represent only the hard parts of creatures. Even these, moreover, are commonly incomplete. The skeleton of an animal may have been scattered by the carnivores that stripped it of its flesh, or erosion may have destroyed the exposed parts before its chance discovery. We cannot, however, be content with the mere description of "vestiges of the dead"; hence paleontologists are ever intent on completing the missing parts and clothing the naked bones, in imagination at least, with flesh and life. Modern museums, therefore, display many fossil skeletons with missing parts restored. In this practice there is no attempt to deceive, for the plaster has a luster different from that of fossil bone and the artificial parts are evident. Nor is the restoration a mere feat of the imagination. The most simple and natural principles are employed in restoring a fragmentary skeleton. For example, if some of the bones in a right limb are lacking but those of the corresponding left limb are preserved, it is obviously safe to model the missing bones as mirror images of those in the opposite limb. Thus, with one entire side of a skeleton incompletely preserved, the whole can be reconstructed with absolute fidelity because of the law of bilateral symmetry. Moreover, the bones of a single skeleton fit together when naturally arranged. Even if they were disarticulated and piled in a heap, it would be no more difficult than solving a jigsaw puzzle to fit them together in their proper places, especially when we have articulated skeletons of similar living types for comparison. If the skeleton lacks part of its ribs, those that are preserved may be sufficient to indicate clearly the contour of the body. The missing ones, it is then evident, must be shaped to fit into this plan. A profound knowledge of comparative anatomy will justify still other restorations that might seem to the uninitiated to be guesswork. For example, suppose but four of the neck vertebræ of a mammalian skeleton have been recovered. The specialist will know that three are missing because all mammals have seven neck vertebræ. Whether the mammal

is an elephant or a giraffe, the length of its neck is controlled by the length of the individual vertebræ, not by their number. If the skeleton is that of a bird or a reptile, on the contrary, no such simple decision can be made, for in those groups the number of neck vertebræ varies. Suppose the skeleton is that of a dinosaur, and several, but not all, of the tail vertebræ are present. The number of missing ones may be inferred from the rate of taper in those that are present.

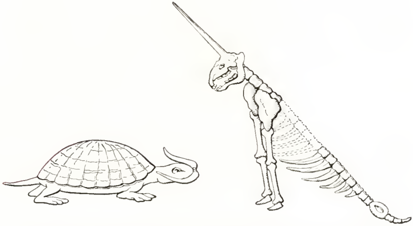


FIG. 30. Early reconstructions based on mammoth bones. Right, reconstruction as a unicorn by Otto von Güricke in 1663; left, reconstruction as "The Missourium" by James Pedder in the London *Times* in 1841. The latter is after G. G. Simpson from *Natural History*.

If the tail is long and slender, there is a chance here for some error, but even so, the mistake will not be great.

In many instances skeletons are found alone and at least partly articulated. When two or more such skeletons are sufficiently complete to be safely identified as belonging to the same species, the missing parts of one may be reconstructed from the other. Thus, if it so happens that the front end of one has been destroyed by erosion and the tail of the other is missing, we can still restore an entire, but composite, skeleton faithfully representing the species. The restoration of fossil skeletons therefore leaves little to guesswork.

However, the clothing of the bones with flesh in lifelike reconstructions does involve powers of imagination, guided by profound knowledge of comparative anatomy. We can visualize extinct creatures only by comparison with living types. If the evolution of life had been utterly haphazard, this procedure would be futile, but few, if any,

of the great groups of animals have become wholly extinct. Genera and species, even families and orders, have died out, but all these had gradually evolved from others, more or less closely related, which still have living descendants. This is one of the reasons why the larger paleontological research institutions are searching the far corners of the Earth for living animals of all kinds. After a careful comparison of the skeleton of an extinct reptile with all related living

FIG. 31. A fantastic reconstruction of various sea monsters. From Thomas Hawkins' *Book of the Great Sea Dragons*, 1840.

types, it is possible to visualize the departed with a vividness far more reliable than mere imagination could supply.

The first attempts at the reconstruction of extinct animals were made before anyone had a very general knowledge of anatomy or comparative morphology. It is not surprising, therefore, that these early efforts were fantastic. The oldest known attempt is the reconstruction of the unicorn by Otto von Güricke, burgomaster of Magdeburg, in 1663 (Fig. 30). It was composed of various Pleistocene elephant bones, the "horn" being, in reality, a tusk. Another early restoration is shown in Fig. 31. From such early attempts, based more on legends and myths than on knowledge of animal life, it is a far cry to the critical modern studies where the necessary muscles are modeled on the articulated skeleton one by one, as the fleshy body is built up, and where attention to the muscular facets on the bone and careful comparison with the musculature of related living types reduce the element of speculation to a minimum.

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A series of short articles giving anecdotes of field experiences. They will convey a good idea of the occurrence of fossils and the nature of the problems met in collecting them.

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Fig. 32. The Tree of Animal Life. Simplified from a colored wall chart by Heintz and Störmer. Reproduced through the courtesy of Ward's Natural Science Establishment. Animals below the wavy white line are aquatic, and those above are adapted to land life.

Chapter 4

THE CONSTANT CHANGE OF LIVING THINGS

"A fire-mist and a planet,
A crystal and a cell,
A jellyfish and a saurian,
And caves where the cave men dwell;
Then a sense of law and beauty
And a face turned from the clod—
Some call it Evolution,
And others call it God."
—William Herbert Carruth.

The Doctrine of Evolution. A thoughtful person can hardly survey the great diversity of life about him without wondering how the

many kinds of plants and animals came to be. And if he contemplates the fossil record and finds that in each geologic age the Earth was inhabited by still different types of life, that question becomes more insistent. Thus far two, and only two, answers have been suggested—the first is Special Creation; the second, Evolution.

The first theory, that of Creation, assumes that each kind of animal and plant was "molded from the dust of the Earth" and "given the breath of life" in its present form, each being a "special" and independent creation. To primitive people who knew but a few hundred kinds of animals and plants, and had no knowledge of biology, this seemed the simplest and most acceptable explanation, as natural as the belief that the Earth was flat and that it formed the center of the Universe about which Sun and Moon and stars revolved. From such early speculation this theory was incorporated in the ancient Hebrew scriptures, and so, for centuries, it exerted a profound influence on the thought of the Christian world.

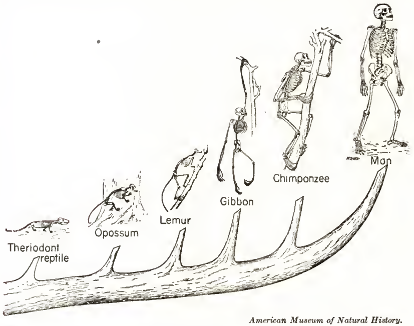
The long and extensive experience of breeding domestic animals and plants suggested a different origin. It is known, for example, that all modern breeds of dog can be traced back to a single species of wild dog, that all our domestic horses have come from one or two species of wild pony, and that the many breeds of cattle have sprung from one, or at most a few, wild ancestors. If it has been possible, within a few thousand years, to change a wild dog into forms as diverse as the whippet, the bulldog, and the poodle, and if, by careful selection and breeding, it has been possible to transform the scrawny wild pony of central Asia into the sleek Arabian race horse, the toylike Shetland pony, and the ponderous Percheron, then we can only wonder if in similar fashion each kind of wild life has developed from some other, by gradual change and specialization. This line of thought led to the doctrine of Organic Evolution, which is the belief that from some geologically remote, primitive form of life all the diverse kinds of animals and plants have developed, each *evolving* from some previous form by gradual and orderly change. According to this conception, all creatures are genetically related, like the members of a great human family, and the degree of relationship of different groups of animals and plants may be represented by the branches of a family tree (Fig. 32).

It may be noted that *evolution* is no less a *special* Creation than that conceived in the Scriptures; it is only a *different method* of creation—one that is still taking place about us and that we can hope to understand. There is still much to learn about the ways and means

by which evolution is brought about, but enlightened people can no longer doubt that it *is* the *method of creation,* and it is now universally accepted as a guiding principle in all fields of biology.

Evidence of Evolution

The evidence of evolution is so varied and so extensive that volumes would be required to review it all, and most of it is too technical for



American Museum of Natural History.

Fig. 33. Series of skeletons from reptile to man. After W. K. Gregory.

simple presentation. Therefore, we can hope here only to suggest the *nature* of the evidence. Our illustrations are chosen from three distinct lines of investigation, the first two biologic, the third geologic.

Comparative Anatomy: Homologous Structures. It is a striking fact that in related groups of animals a given organ or anatomical structure is built on the same plan. This is illustrated repeatedly in Fig. 33, for, in spite of the impressive differences between reptile, lemur, and man, the skeleton in all three is constructed on the same fundamental plan, and its elements can be matched bone for bone. The fore limb in each includes a single upper arm bone (humerus),

a pair of forearm bones (ulna and radius), a series of wrist bones (metacarpals), and five digits.

If we extend the comparison to distantly related mammals such as the bat, the seal, and the dog (Fig. 34), we find great modifications of the limbs for different habits of life; yet the arm of a man, the wing of a bat, the flipper of a seal, and the fore leg of a dog are built with the same skeletal elements, the dissimilarities being due essentially to differences in size and proportions of the individual bones.

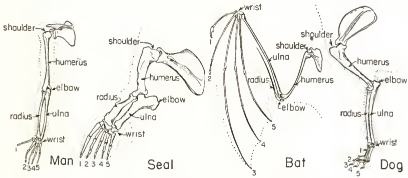


FIG. 34. Homologous structures in left fore limb of man, seal, bat, and dog.

Organs that thus agree in fundamental structure are said to be *homologous.*

A study of the muscles and of the internal organs would greatly multiply the examples of homologous structures in the animals mentioned. Such likenesses indicate kinship and descent, with modification, from a common five-toed ancestor; they are inexplicable on any other basis.

Vestigial structures—those that have lost their function—afford perhaps the most telling evidence from comparative anatomy (Fig. 38). Such, for example, are the ear muscles in man, which are homologous with those that move the ears of the lower mammals, but in most humans are no longer under voluntary control and serve no useful purpose. Another vestigial structure is the human appendix, which seems to be only a source of danger, although its homologue in many lower animals is an important part of the digestive system. About 180 such useless features have been recorded in the human body. One of the striking and unfortunate misfits of our anatomy is the way in which the viscera are supported in the body cavity. All the mammals, save man and the apes, walk on all fours, with the body in a horizontal

position, and the delicate mesenteries that hold the various organs in place are well fitted to this posture. In standing upright, however, man has brought the body into a vertical position in which the mesenteries, supporting the viscera and arranged as in the quadrupeds, are inadequate and inefficient. As a result, human beings suffer from "fallen stomach," prolapse of the womb, paunchiness, and hernia. Surely, if a body were created *de novo,* it would not be endowed with useless and dangerous appendages *aping* those which are functional in other animals; and the human body would hardly have been given the most inefficient and troublesome visceral support of all the mam-

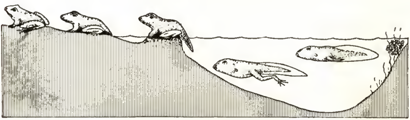


Fig. 35. Metamorphosis of the frog. From right to left: cluster of eggs; tadpoles showing two late stages in the budding of limbs; three early stages of terrestrial life showing the gradual loss of the tail in the young frog.

mals, one that is efficient for the quadrupeds but not for man. Such vestigial structures admit of no other rational explanation than that man is related to other animals by common descent from ancestors in which these structures were functional.

Embryology: The Law of Recapitulation. Each individual begins as a single cell and by repeated cell division grows and passes through a remarkable series of embryological and juvenile stages before assuming its normal adult form. This orderly sequence of developmental stages constitutes its *ontogeny.*

One of the great biological discoveries of the last century is the fact that the ontogeny repeats briefly (and in many cases imperfectly) the racial history. Stated as a natural law, *ontogeny recapitulates phylogeny.* The amphibians (for example, the frog and the salamander) provide an illustration of such recapitulation (Fig. 35). They lay their eggs in the water, and these eggs hatch into tadpoles that are in essential respects fishlike, breathing by means of gills and having no lungs or limbs. But during growth the gills are resorbed, lungs are formed, legs bud out from the body, and, after a transition period, the animal leaves the water to spend the rest of its

days on land. This remarkable metamorphosis implies that the remote ancestors of the amphibia were fishes, from which they descended by migrating from the water to the lands, with all the modifications which that migration imposed.

Recapitulation really means that an animal has inherited from its ancestors a certain ontogeny which it repeats up to the point at which its own peculiar specialization begins. The amphibians inherited from

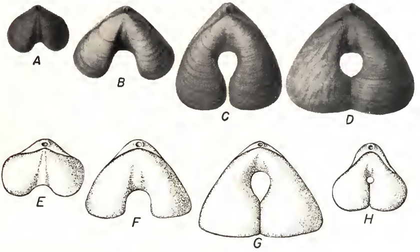


FIG. 36. Individual and racial history of the keyhole brachiopod, *Pygope*. *A–D*, individual shells, representing four stages of growth in a single species (*Pygope diphyoides*); *E–H*, adult shells of distinct species from four different geologic ages, showing the racial history. *E*, *F*, and *G* are from successive Jurassic ages, and *H* from the early Cretaceous.

their remote ancestors, the fishes, the capacity to lay only small eggs without much yolk and without shells. Such eggs can survive and hatch only in water, and the young, of necessity, breathe by means of gills. The amphibians were never able to improve on this habit and so, throughout the ages, have returned annually to the water to spawn.

Many fossil shells preserve a record of their own ontogeny. Consider, for example, the keyhole shell, *Pygope*, among the Jurassic brachiopods (Fig. 36). The adult shell has a hole passing through its middle, like the hole in a doughnut. A young one, however, has the shape shown in *A;* a slightly older one, *B;* and a half-grown shell, *C*. The lines of growth on the adult shell, *D*, recording its margin at many stages of development, show that it passed through all the shapes preserved in the young shells. It is obvious that the very young shell was not perforated but had a shallow notch at its front

margin, and during growth it became deeply bilobed and the notch became deep and rounded; eventually the lobes converged and grew together, thus transforming the notch into a hole. This ontogeny would imply that *Pygope* descended from a remote ancestor which at maturity was shaped much like the young shell, *A*, and that, during the ages, the race underwent progressive changes of shape similar to those repeated in the ontogeny of *Pygope*. In actual fact, a series of species has been found in successive horizons in the Jurassic and Cretaceous rocks of Europe which prove that the racial development *did* follow this course (Fig. 36, *E-H*).

Another illustration of ontogeny is afforded by the straight-shelled ammonite, *Baculites*, of late Cretaceous age (Fig. 37). Although most

FIG. 37. Shell of *Baculites compressus*, a straight ammonite whose tip implies that its remote ancestors were coiled. This is a young shell enlarged about 10 diameters. The transverse markings are lines of growth on the surface of the shell.

of the shell is straight, the tip is tightly coiled, and the inference is, therefore, that its remote ancestors were coiled (as, in fact, nearly all ammonites were).

In so far as the early ontogenetic stages are inherited from ancestors, they clearly indicate the general nature of the ancestral stock of any animal. Thus, closely related animals should be closely alike in their early ontogeny, and, conversely, animals that are closely alike in their youth are probably genetically related, even though they specialize and become dissimilar at maturity.

Paleontology: The Documentary Evidence. If life has evolved gradually since early geologic time, the fossils preserved in successive formations should record many intermediate stages between forms now widely differentiated, and should provide connecting links between even widely distinct stocks of animals and plants. In following chapters we shall have occasion to note many such cases, some of which have played a major role in establishing the doctrine of descent. In the study of embryology and comparative anatomy we have only circumstantial evidence of evolution, but in the fossil remains of evolving series we have the actual documentary evidence that the changes have occurred.

The origin of the keyhole shell discussed above is an example; the ontogeny led us to infer how the perforation developed, but the discovery of fossil shells representing the inferred changes in successive Jurassic and Cretaceous formations affords the documentary proof in the case.

American Museum of Natural History.

FIG. 38. Skeleton of hind legs of modern horse.

The skeleton of the horse's leg displays interesting vestigial structures whose significance is clearly shown by the fossil record. In the hind leg, for example, if we begin with the hip joint (Fig. 38), it is easy to identify the thigh bone and the knee cap, and below these the paired lower leg bones, the tibia and fibula. The hock is really the heel, as shown by its relations to the short tarsals, and below the latter are the elongated toe bones. From this examination we may conclude that the horse walks on the *end* of one toe and that the lower part of the leg has been greatly lengthened as the heel came up off the ground (please examine also Fig. 294, p. 462).

Now in primitive mammals, and even in the specialized ones that use their hands and feet for grasping or digging, the paired lower limb bones are subequal in size and provide for a rotary motion of the hands and feet. But in the horse, which can bend its leg only fore and aft at the heel, the fibula is reduced to a mere sliver, and its lower end does not even make contact with the foot bones. The

presence of this vestigial fibula implies, however, that the remote ancestor of the horse had a less specialized limb with freer movement of the foot. And on each side of the main toe bone (the cannon bone) there is a slender bone known as the *splint*, which can be nothing but the vestige of another toe. The splint bones clearly imply that the ancestor of the modern horse had three toes, as do the rhinoceros and the tapir.

The series of fossil horses recovered from successive Cenozoic formations in the western United States proves this inference to be true beyond any doubt. For example (Fig. 295), all the fossil horses from the Pleistocene, and most of those from the Pliocene, are like the modern horse, but *all* those of the Miocene have three toes on each foot. In these, however, the side toes are slender and in most species apparently functionless, probably dangling like the dew claws of cattle. In the underlying Oligocene beds, on the contrary, the three toes are subequal in size on each foot and all shared in bearing the animal's weight. Finally, in the still older Eocene strata, vestiges of a fourth toe have been found in the front feet. No fully five-toed ancestor has yet been identified, but there can be no doubt that such a one existed. Illustrations of the paleontological evidence of evolution could be multiplied to any length, for they form the essence of the geological history of life.

Ways and Means of Evolution

Variation. Heredity is the principle that "like begets like," the parent passing on to its offspring all its distinctive characters. However, no individual is exactly like its parent, nor is it precisely like any of its brothers and sisters, even of the same brood; and commonly there is an appreciable variation among individuals of the same species. Thanks to recent progress in the science of genetics we now understand a good deal about the way in which variations arise, but the facts are too complex and technical for brief presentation. Regardless of the cause, experience indicates that, in spite of the heredity principle, variations, mostly slight, occur in each new generation.

The Struggle for Existence. All kinds of animals and plants produce more offspring than can possibly survive. Many of the lower animals lay thousands or even millions of eggs each year—the salmon as many as 28,000,000 and the oyster more than 100,000,000—and a plant such as the elm or maple tree produces innumerable seeds. This

means that among such organisms only one out of millions lives to maturity; otherwise the population of any species would rapidly increase. Even in the higher animals such as man, where few offspring are born, more die young than survive to maturity.

Thus, throughout Nature there is an intense and never-ceasing struggle on the part of all kinds of organisms to exist and to grow and to reproduce their own kind. The struggle is against the environment, against enemies that devour or those that cause disease; commonly it is against members of the same kind, in competition for food, or even for "a place in the sun." Life's struggle is exceedingly harsh toward the young, and success is the rare exception.

Natural Selection. In a struggle so severe, any advantage, however slight, may decide between life and death. And of the many trivial variants that appear in any species, some will have an advantage and will tend to survive, while others, less favored, will tend to be exterminated. For example, if the species is an animal living in an environment where fleetness is necessary to escape carnivorous enemies, the slow and the underdeveloped young in the herd have little chance to reach maturity, whereas, on the average, the most precocious will survive and pass on their characteristics to new descendants. In this way Nature selects, as a breeder of stock might do, eliminating the unfit (unfit for a particular environment) and permitting only the fit to continue the race. And so, in spite of endless and random variations from generation to generation, only selected ones will survive. By this method Nature has evolved new species from old, to meet new or changed environments.

A single illustration may serve to show how such adaptations are produced (Fig. 39). The crossbill, which ranges over Europe from the Alps to Siberia, lives on the seeds of evergreens. In the Alps it feeds on pine cones, which are tough and hard and require a stout, thick bill if the bird is to break them apart and extract the nut. In Siberia, however, it has to feed on cedar cones instead of pine, and in these the seeds lie deeper but are not so well protected, and here a longer, more slender beak is a decided advantage. Now when the crossbill appeared in Europe (whether by migration or evolution), those birds that varied toward long slender bills could not survive through a hard winter in a pine-clad region where the competition for food was keen, because their fragile beaks could not break enough pine cones. The birds with short, stout beaks fared much better. Conversely, the short-beaked birds could hardly survive in the cedar forests because they could not reach the nuts; there, the birds with longer and more

slender beaks survived. Thus it has come about that, through many generations of natural selection, the crossbill of Siberia has a slender beak with the upper jaw protruding about one-tenth of an inch beyond the lower, whereas the crossbills of the Alps have short, stout beaks.

FIG. 39. Adaptive specialization of the beaks in the crossbill, *Loxia*. The parrot crossbill (left) feeds on pine cones; the common crossbill (center) feeds on spruce cones; and the Himalayan crossbill (right) feeds on the small soft cones of the larch. Natural size. Data from David Lack.

Illustrations could be multiplied ad infinitum if space permitted, for the whole complex of life is a maze of adaptations to special habits and conditions.

Many biologists believe that new species arise from old through gradual change forced by natural selection operating on random micromutations. Others believe that from time to time more profound changes in the genes may cause megamutations great enough to start a new species at one jump. There are other factors that may also play a part. As to the general doctrine of evolution by descent with modification, there is no longer any doubt of its validity, but the ways and means are still the subject of intensive research and hot debate.

Collateral Reading

Organic Evolution; by Richard S. Lull. 744 pages. The Macmillan Co., New York. Rev. ed., 1947.

The Origin of Species; by Charles Darwin. 1859.

Evolution for John Doe; by Henshaw Ward. 342 pages. The Bobbs-Merrill Co., Indianapolis, 1925.

A popular account by a layman for the layman.

The Evolution of Earth and Man; by Joseph Barrell, Charles Schuchert, and others. Edited by George A. Baitsell. 476 pages. Yale University Press, 1929.

The chapter on "The Mechanism of Evolution," by W. R. Coe, summarizes a subject only briefly touched upon in our chapter.

Genetics, an Introduction to the Study of Heredity; by Herbert Eugene Walter. 412 pages. The Macmillan Co., New York, 1928.

An entertaining and lucid volume.

Genetics and the Origin of Species; by T. Dobzhansky. 346 pages. Columbia University Press, 1937.

Clearly written but technical.

II. BEFORE THE CAMBRIAN

Chapter 5

ORIGIN OF THE EARTH

"From Chaos' start the eons spread
And grind on slowly but exceeding small
To make a landscape."

—Freeman Wood.

From the earliest times men have speculated upon the origin of this world in which we live, and legends of a creation are known to almost every race and tribe. Many of these beliefs are fantastic, but their very existence shows that the Earth's beginning has been an endless challenge to the mind of thinking man.

Before the Renaissance there was no check upon such speculation except authority and tradition. Men then had no real knowledge of the nature of the sun and stars or of the natural laws that govern the Universe. There is still no hope that we can go back to first causes—the origin of matter and the beginning of time may lie forever beyond our understanding—but it is now clear that the Earth, as such, is not eternal, and we can hope to understand how and when it was molded out of stardust into a planet and set revolving about the Sun. Our present knowledge of the nature of matter, and of the physical and chemical laws that operate everywhere, has recently made it possible to tap the hidden reservoir of subatomic energy; these laws are precisely the tools we may also use in the scientific attack on the problem of the origin of the Earth.

Close Relatives: The Solar System

It is now clear that the Earth and other members of the Solar System have had a common origin. They appear to represent masses of material that were torn apart by a colossal stellar catastrophe more than 2,000,000,000 years ago. To form a background for this cosmic spectacle, we must first make a brief excursion into the field of astronomy.

At the center of the Solar System is the Sun, and revolving about it are nine planets with their moons, more than a thousand planetoids, and the comets and meteors (Fig. 40). These will be examined briefly in turn.

The Sun. The Sun is a star 860,000 miles in diameter and so hot as to be self-luminous. Its temperature is about 6000° C. at the surface, increasing to about 20,000,000° C. at the center. The surface temperature alone is sufficient to vaporize any known substance, and thus, although it is made of the same chemical elements as the Earth,

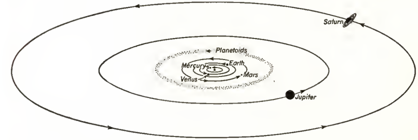


FIG. 40. The Solar System. Oblique view from above, showing the nearly circular orbits of all but the three outermost planets. The spacing of the orbits is drawn to scale, the size of the planets being represented on a different and greatly exaggerated scale. It is impossible to represent the Sun on this exaggerated scale, but its size, relative to that of the planets, is shown in Fig. 42. Adapted from Gregory, *The Vault of the Heavens* (Dutton and Co.).

the Sun is entirely gaseous and expanded so that its average specific gravity is scarcely one-fourth that of the Earth.

The energy radiated from this white-hot globe provides the Earth with life-giving warmth, enables plants to create organic compounds, lifts the vapors that return as rain, sets the atmosphere in motion, and thus motivates all the erosive forces on the planet. If for no other reason, therefore, the Sun would be a fascinating object of study.

The Sun's energy is radiated in all directions into space, and only about one part in two billion is intercepted at the Earth. It amounts to 70,000 horsepower per square yard of the Sun's surface and has not flagged or varied greatly for more than a thousand million years.

The *source* of the Sun's heat is a problem that could not be solved until we had discovered the secret of subatomic energy. Chemical combustion would not suffice, for if the Sun were made entirely of coal and oxygen in combustible proportions and were to provide energy at this rate, it would have been entirely consumed and transformed into carbon dioxide and water vapor since the beginning of the Christian

era. Moreover, the spectroscope clearly shows that neither carbon dioxide nor water exists in the Sun.

The discovery of radioactivity shortly before 1900 revealed a new source of heat. The disintegration of the radioactive elements was found to be accompanied by the slow but continuous emission of radiant energy. Although this energy is given off slowly, the total amount vastly exceeds that attainable through the chemical combustion of a like mass of any substance. *Uranium* and *thorium,* the chief parent elements of the radioactive families, are widely disseminated in the rocks of the Earth's crust and now appear to be an adequate source of the Earth's internal heat, including that manifested in volcanism. Indeed, it is fortunate that they are among the rarest of substances in the Earth, for if they were common the entire crust would be molten.

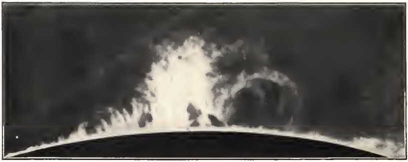
This now familiar source of energy involves the breaking down of the largest and most complex atoms into simpler ones; but recent studies in atomic physics have shown that an even greater reservoir of energy lies in the opposite direction, namely, the building up of the simplest elements into more complex ones, for example, *hydrogen* into *helium.*[1] The union of four atoms of hydrogen would produce one atom of helium and at the same time liberate a relatively large quantity of radiant energy. Actually, the hydrogen atoms probably do not unite directly, but instead attach themselves one after another to an atom of carbon which is thus built first into an atom of nitrogen and then of oxygen. From the latter, in turn, the united atoms of hydrogen split off as an atom of helium, freeing the original carbon, which thus acts merely as a catalyst. This has not yet been accomplished experimentally because it will require a temperature of about 20,000,000° C. to make atoms of hydrogen unite, and we can not generate such heat nor could we contain it if we did, for the most refractory crucible would explode into gas. Such, however, is the temperature that obtains deep within the Sun and the stars, where hydrogen is being built up into helium.[2]

As the spectre of atom bombs hangs over us, we are inclined to regard atomic energy with dread, little realizing that our world would be lifeless without it. It has already been usefully employed in ways of peace since the beginning of human existence—for sunshine is pure atomic energy!

The visible white disc of the Sun is the surface of its body or *photosphere,* which the telescope reveals as a billowy surface of seething white-hot gases. Outside this is a rarer atmosphere of cooler gases

5000 to 10,000 miles thick, known as the *chromosphere* because of its brilliant reddish color. From its surface arise the *solar prominences* (Fig. 41) that leap out like enormous tongues of crimson flame and, attaining heights of 20,000 to 500,000 miles, sometimes rise with velocities as great as 100 miles per second. They are wisps of light gases, chiefly hydrogen and helium, driven up by the radiation pressure of sunlight.

Spectral lines in the Sun's light permit the certain identification of many of the chemical elements known on the Earth, and there is now



Frederick Slocum, Van Vleck Observatory.

FIG. 41. A bit of the Sun's rim, showing a solar prominence. The chromosphere appears above the black mask used to block out the Sun. The prominence has a height of 60,000 miles. Taken October 10, 1910.

every reason to believe that the Sun contains all the chemical elements present here and no others.

Contrary to the belief of the ancients, it is now known that the Earth revolves around the Sun. However, it must not be supposed that the Sun is stationary. It rotates like a top on its own axis, turning once in about 25 days, and, at the same time, it is rushing along through space, with its retinue of planets, at a velocity of about 12 miles per second.

The Planets. The planets are nine in number, and their relative sizes are shown in Fig. 42. They fall into two decided groups, the minor planets (Mercury, Venus, Earth, and Mars) being relatively small, solid, and earth-like bodies, whereas the major ones (Jupiter, Saturn, Uranus, and Neptune) are vastly larger and mostly gaseous. (Pluto, the most remote planet, is believed to be solid and comparable in size to the minor planets. It may not be genetically related to the other planets.) They all revolve in nearly circular, concentric orbits, and are regularly spaced so that, with two or three exceptions, each is nearly twice as far as the next nearest from the Sun (Fig. 40). The

first exception to this rule is that the minor and major planets are separated by a wide belt where a planet should be but where instead we find the planetoids. Another exception is that the remote planet Neptune is not spaced quite far enough. The distance of Pluto is on the average about 40 times that of the Earth from the Sun (varying between 30 and 50 times as a result of its notably eccentric orbit).

Earth is seen to hold an intermediate position among the planets in several regards. In size it is the largest of the minor planets, with a

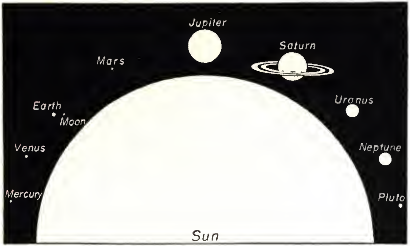


FIG. 42. Chief members of the Solar System, represented on a uniform scale. The planets are arranged from left to right in order of their distance from the Sun. Modified from Kayser's *Abriss der allgemeinen und stratigraphischen Geologie* (F. Enke).

diameter of 8000 miles compared to 3000 miles for Mercury and 4200 miles for Mars, but it is far exceeded by the giants Jupiter (88,600 miles) and Saturn (74,100 miles).

It also occupies an intermediate position in regard to its distance from the Sun, Mercury being about one-third as far, Jupiter five times as far, and Neptune about thirty times as far.

The Earth excels, however, in one respect—it is the densest of the planets, having a specific gravity of 5.5, whereas that of Mercury, Venus and Mars is slightly less and that of the major planets much less. Saturn has the lowest specific gravity, 0.72.

Satellites. The satellites (moons) of the planets are significant in any explanation of Earth's origin. Mercury and Venus have no moons, but Earth has one, Mars two, Jupiter eleven, Saturn nine,

Uranus four, and Neptune two. None has been discovered for Pluto. Our own Moon is exceptional in having greater mass than any other satellite, and in being relatively large as compared with its planet. It is intensely interesting, moreover, because it is much the nearest to us of all the heavenly bodies and the only one whose surface can be easily observed.

C. L. Stearns, Van Vleck Observatory.

FIG. 43. The Moon at first quarter. The large dark spots are relatively smooth lava plains, not seas as the ancients supposed. The circular depressions are enormous volcanic craters.

Direct photographs through large telescopes (Fig. 43) reveal the fact that the Moon has a barren surface and is utterly devoid of atmosphere. Its great, flat lava plains, supposed by the ancients to be seas (and therefore named *maria*) are entirely without water. The reason for this we now know to be that the moon is not large enough to have sufficient gravity to hold an atmosphere. If it were surrounded by gases, they would leak away into space just as gas would escape from an open vessel placed on a classroom table. In fact, the crater-scarred surface of the Moon gives the most striking display of volcanic features, and every crater must at some time have belched forth gases in great volume; yet the complete absence of stream valleys clearly indicates that it has never had a rain-bearing atmosphere. Evidently the gases escaped almost as fast as they issued at the Moon's surface. No evidence of present eruptions has ever been observed, though they would be plainly visible to us if they occurred, and it appears, therefore, that the Moon is now lifeless and changeless.

The satellite systems of Jupiter and Saturn are like miniature replicas of the Solar System, but they present one exceptional feature of special significance, namely, retrograde motion. In general, the Solar System is organized so that its elements revolve counterclockwise as viewed from the North Pole. This is true of all the planets,

all the planetoids, and nearly all the satellites. However, the eighth, ninth, and eleventh satellites of Jupiter and the ninth of Saturn revolve in the opposite sense and are therefore described as *retrograde*. It may be signficant that these are the outermost satellites of their respective systems and are far removed from their planets.

All the satellites thus far considered revolve like the planets, nearly in a common plane, but those of Uranus and Neptune revolve in orbits obliquely crossing this plane at high angles.

Planetoids. In a broad belt between Mars and Jupiter there are many small planet-like bodies, of which about 1200 have been ob-

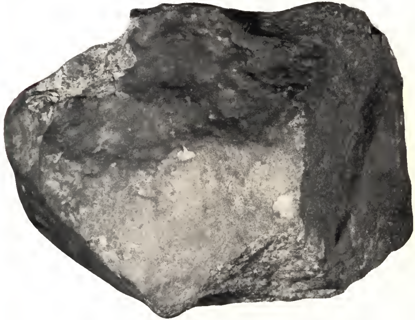
Ferdinand Ellerman, Mount Wilson Observatory.

FIG. 44. Halley's comet, May 5, 1910.

served, ranging in size from a diameter of 485 miles down to 5 or 10 miles, which is the limit of visibility with present telescopes. These are the *planetoids*. They are too small to hold an atmosphere and are therefore lifeless solid bodies, each revolving in its own orbit about the Sun. Many of these orbits are decidedly elliptical, so that the planetoids occasionally cross paths.

Comets. A comet is a luminous object (Fig. 44) normally displaying a well-defined head and a long tail. Comets revolve about the Sun in greatly elongated elliptical orbits. Each has its own path, but as a group they show no common motion and do not lie in the general plane of the system. The head of the comet is made of solid matter like that of a meteor (see next paragraph), and its luminous envelope and long tail appear to be composed of widely separated molecules of gas driven off from the head by the repellent force of the Sun's radiant energy. This interpretation rests partly upon the fact that in the comet's journey around the Sun the tail is constantly directed away

from the Sun, streaming behind as the comet approaches, then swinging rapidly through a great arc at the perihelion and rushing ahead as the comet recedes. Comets frequently cross the planetary orbits and occasionally come near collision with a planet. On such an occasion in 1886 Brooks's comet came so near Jupiter that it was drawn



Yale Peabody Museum.

Fig. 45. The Weston meteorite. This specimen was one of several observed to fall near Weston, Connecticut, on December 14, 1807. Its description by Benjamin Silliman then attracted much attention, for it was the first meteorite to be observed to fall. About $\frac{2}{5}$ natural size.

from its accustomed course (with a 27-year period) and thrown into a smaller orbit in which it now returns every 7 years. The fact that Jupiter's satellites were not disturbed proves that the mass of the comet is not great.

Meteors. The so-called shooting stars are not stars but small pieces of stony or metallic material whose surfaces are heated to incandescence as they dash into our atmosphere at velocities of some miles per second and suddenly meet with great frictional resistance. Most of them are consumed and dissipated into gas and smoke in their downward plunge, but occasionally one reaches the Earth and is recovered. As luminous objects in the sky these are called meteors, but

after falling to Earth the solid objects are known as *meteorites* (Fig. 45). They are of particular interest because they seem to be the scattered fragments left over after the creation of our Solar System.

Earth's Place in the Universe

Nature and Distance of the Stars. The stars that dot the heavens are all self-luminous suns. The average diameter is approximately 1,000,000 miles, but there are greater giants like Ras Algethi and Antares with diameters of 690,000,000 and 390,000,000 miles respectively. They appear to us as tiny points of light only because of their enormous distances. Our Sun is about 93,000,000 miles from the Earth, and its light requires nearly 8 minutes to reach us, traveling at the velocity of 186,000 miles per second. But it takes light over 4 years to reach us from the nearest star and 10 to 500 years to come from the brighter stars about us. Many faint stars are thousands of light-years away (a light-year being the distance light will travel in 1 year at a velocity of 186,000 miles a second).

Our Galactic System. The stars are not infinite in number nor indefinitely scattered through space. The great telescopes indicate that they number possibly 100 to 500 billion and that they constitute a great system occupying a definite part of space, circular in plan, and elliptical in section like a great lens. Presumably the system rotates on its axis like a colossal pinwheel. The Milky Way defines the plane of the system, and the great telescopes reveal this belt of faint light to be made of innumerable stars so remote as to be invisible individually to the naked eye. We are relatively near the center of this great lenticular system and, looking out toward its vast periphery, we see the distant stars apparently crowded only because we are looking across the greatest diameter of the system. Our stellar universe therefore constitutes the system of the Milky Way or the Galactic System (Gr. *galaktinos*, milky). It is believed to have an equatorial diameter of the order of 200,000 light-years and a polar diameter probably one-tenth as great. For a long time the Sun was supposed to be very near the center of the Galaxy, but the most recent researches indicate that it is about 40,000 light-years from this point.

The mind can not grasp such distances and fails to comprehend the isolation of the Solar System among the stars. Let us therefore divide the scale of Nature by a thousand million. The Sun may then be represented by a push-ball 4½ feet in diameter, and the Earth by a marble ½ inch in diameter at a distance of only 500 feet. The entire

Solar System would have a diameter of 3 miles, but the nearest star, represented by another push-ball, would be 25,000 miles away. And the average distance between the stars on this scale would be tens of thousands of miles!

Beyond our Galaxy in turn lie others which constitute the spiral nebulæ (Fig. 46). They are aggregates of stars like our own Galactic

N. U. Mayall, Lick Observatory.

FIG. 46. Spiral nebula in Andromeda, seen in oblique view. This is the only one of the spiral nebulæ clearly visible to the unaided eye and is the most remote object to be seen without a telescope. Its distance is approximately 900,000 light years.

System but isolated so far out in space that we see them as faint, hazy points of light visible only through the telescope. Herschel compared them to islands in a sea of space. They are known as spiral nebulæ (Lat. *nebula*, cloud) because of their obvious spiral form and the fact that they commonly appear as cloud-like, luminous objects.

Hypotheses of Earth Origin

Several hypotheses have been advanced to account for the origin of the Solar System, but as yet none is free of serious objections.

Even so, the best of them deserve brief study because they represent the present trends of thought about one of the greatest unsolved problems of our world. Furthermore, our geologic thinking is commonly influenced, directly or indirectly, by tacit assumption as to the origin and pregeologic history of the Earth. Such a common phrase as "the crust of the Earth," for example, stems from the conception that this planet was originally molten and, in cooling, crusted over at the surface. Even the far-reaching belief that fold mountains have arisen because of shrinkage of the Earth's interior rests on the assumption that the Earth was once hotter than now and is slowly cooling.

The Nebular Hypothesis of Laplace

The first explanation to merit serious consideration as a scientific hypothesis was suggested by the philosopher Kant and later developed, about 1796, by the French astronomer Laplace, who tried to show how a hot gaseous nebula, in cooling, would automatically develop into a solar system. This seemed a simple explanation of most of the features of our Solar System known at the time, and Laplace's hypothesis was widely acclaimed during the nineteenth century; in the light of our present knowledge, however, it has only historic interest.

HYPOTHESES OF SOLAR DISRUPTION

By 1900 the weaknesses of Laplace's hypothesis had become so evident as to make it seem improbable that a nebula could automatically develop into a solar system. Then two American scientists, the geologist T. C. Chamberlin and the astronomer F. R. Moulton, conceived and developed the hypothesis that the Sun, originally without planets, had at some remote time nearly collided with another star and as a result had been partially disrupted, the fragments gathering about it to form the several members of the Solar System. This conception is the basis of the leading modern theories of the origin of the Solar System.

The stars are remotely spaced, but they travel at velocities of many miles a second and move in diverse directions. Fortunately, the chances of collision or even of close approach are remote. If the improbable did happen, the mutual attraction would mount as two stars approached, and each would be drawn toward the other. If they did not actually collide, the course of each would bend sharply toward the other until the moment of passing and then would gradually straighten out in some new direction as the stars receded from one another and the forces of attraction died down. And if they came

within a million miles or so of each other, it appears certain that tidal stresses at the moment of passing would cause each to be partly disrupted.

The principle of the tidal forces is illustrated in Fig. 47, which represents the simple case of a planet, such as Mercury, revolving about the Sun. In this instance, Mercury is held in its course by two forces, one driving it ahead in its orbit and the other drawing it toward the Sun. If the first alone were acting, Mercury would be driven away

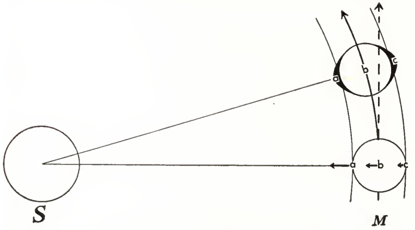


FIG. 47. Diagram to explain the tidal forces in a planet (M) revolving about the Sun (S).

into space along a straight line (broken line); if solar attraction alone were acting, it would fall directly into the Sun. The size of its orbit is determined by the ratio of these forces. If, for example, the Sun's attraction were increased, the planet would be drawn into a smaller orbit, but if it were decreased, Mercury would fall away through centrifugal force into a larger orbit. Now, since the force of attraction varies inversely as the square of the distance from the Sun, it is evident that a particle, *a*, on the near side of Mercury, is actually attracted more strongly than a particle, *c*, on the opposite side. The planet as a whole, of course, obeys the intermediate or average force exerted on all its particles, but the side near the Sun tends to be drawn into a smaller orbit and is thus pulled up into a low tidal bulge facing the Sun, while the opposite side, held with less than the average pull, tends to fall away into an equal tidal bulge opposite the Sun.

The height of the tide depends, of course, not on the total solar attraction but on the differential attraction on opposite sides of the

planet. Since the planets are millions of miles from the Sun and only a few thousands of miles in diameter, there is a very slight difference in the distance (hence in the attraction) between far and near side, and the tidal bulges are very low.

In the case of two stars coming within a million miles or so of each other, however, the differential pull on opposite sides of each would rise to a large fraction of their total attraction as each swung sharply around the other in passing, and the tidal forces would then reach the critical point of disruption. At that time the tidal bulges in a gaseous star like the Sun would rise into cones, from which matter would stream forth as from a syringe bulb squeezed at the middle.

The subsequent behavior of this ejected material and the method by which it was gathered up and organized into the Solar System are still the subject of investigation and debate. We shall briefly examine the two leading hypotheses.

The Planetesimal Hypothesis

Chamberlin (Fig. 48) and Moulton believed that explosive forces within the Sun played an important role in the tidal disruption. They considered the solar prominences to be evidence of colossal explosions in the Sun, due to its extremely high temperature. Accordingly, they argued, when the tidal bulges approached the stage of disruption, such explosive forces would drive the material out in great jets or *bolts*, instead of in a steady stream of gas. If so, each bolt of gas would behave as a unit, being drawn by the passing star and set rotating in a highly elliptical orbit about the Sun. According to this view, the disruption would have resembled in a very real way the explosion of a gigantic pinwheel throwing off sparks in the plane of its rotation.

It is postulated that many bolts were ejected from the ancestral sun, some large and some small, but that ten of the largest served each as the nucleus of a planet, and another broke up to form the planetoids, while the smaller ones formed satellites and meteors, as well as a vast amount of scattered material that was later gathered up by the planets. It is also postulated that five of the ten great bolts were expelled from the tidal bulge facing the passing star, and that these were drawn farther away to form the major planets, while five ejected from the opposite side, and not drawn out by the passing star, remained nearer the Sun to form the minor planets and the planetoids. Thus we find an explanation of the spacing and of the contrast in size and density between the major and minor planets.

Formation of a Solar Nebula of Planetesimals. If hot gas was thus expelled in great jets from the Sun, each bolt would cool rapidly as it rushed out into space and would tend to condense into liquid and then into solid particles, while at the same time the sudden release from pressure would favor rapid expansion and dissipation of the gases. The net result, according to Chamberlin and Moulton, was a swarm of solid particles (like meteorites) in a halo of cool gases. The solid particles they called *planetesimals*. Such a swarm of planetesimals formed the nucleus of each planet. However, the bolts that formed the major planets, being made of the lighter elements, must have remained largely gaseous. Moreover, they were large enough to remain intact because of their internal attraction, whereas the minor planets were made largely of planetesimals and were too small to hold most of the gaseous material.

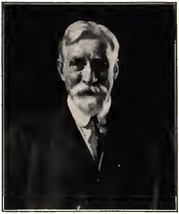


Fig. 48. Thomas Chrowder Chamberlin (1843–1928), pioneer student of Earth origin through disruption of the Sun.

Within a few years after the disruption, the passing star had receded again into space, the tidal forces had died down, and the erupted material was left to fall back toward the Sun. Meanwhile, however, the pull of the passing star had drawn each particle in its wake and started the whole system revolving. Most of the returning particles, therefore, missed the Sun in their fall and dropped into elliptical orbits in which they continued to revolve. Each had its independent orbit, whose size depended on the force of the explosion from which it sprang, the nearness of the disturbing star when its bolt was ejected, and various other factors. Since all lay nearly in one general plane, these innumerable solid particles swarmed about the Sun in a sort of miniature spiral nebula.

Growth of the Nuclei into Planets. In this solar nebula the intersection of orbits would have made frequent collisions inevitable. In this way the few large nuclei must have grown at the expense of the planetesimals which they swept up exactly as the Earth now assimilates the meteorites it intercepts. At first the amount of finely scattered material was probably very great, and the larger nuclei may have been illuminated by a constant rain of meteors.

It can be demonstrated that in the union of two particles traveling in elliptical orbits, the resultant orbit is a compromise between the two and more nearly circular than either; hence the continued growth of the nuclei would result in more nearly circular orbits. In this respect the theory finds striking confirmation in the fact that the planets have almost circular orbits, whereas the planetoids, which are much smaller, show marked eccentricity, and the meteors and comets still travel in highly elliptical paths.

Slow Growth and a Solid Earth. According to the Planetesimal Hypothesis, the material of which the Earth is formed had cooled to solid particles within a very short time after its ejection from the Sun. The nucleus may, of course, have retained considerable heat, but the major part of the planet has been built of small solid particles. In the collisions between planetesimals and nuclei, heat was of necessity generated by the impact, but if the fall of planetesimals was not too frequent, each would cool before another struck in the same place. Chamberlin and Moulton have strongly advocated the view that the growth of the nucleus was slow, requiring many millions of years for its completion, and that the Earth was not molten at any stage of its development, its surface having been cool from the beginning. They recognize as an alternative, however, the possibility that the infall was sufficiently rapid to produce a molten surface.

Primordial Atmosphere. If the Earth was formed by slow accretion of solid particles, it could have had no atmosphere until it attained a diameter of more than 2000 miles. With greater mass, it should have retained gases gathered from its path and those generated by volcanic activity within. At first its gaseous envelope must have been thin and rare, increasing gradually to its present condition. It is possible that free oxygen existed from the first, or, if not, that primitive plant life was established long before the Earth had reached its present size, and by photosynthesis had broken down carbon dioxide and freed liberal amounts of oxygen.

Objections to the Planetesimal Hypothesis. During the last four decades the Planetesimal Hypothesis has been subjected to searching criticism and now appears to have serious shortcomings, only a few of which can be presented here.

In the first place, there is now convincing evidence that the Earth passed through a completely molten stage. As explained in Chapter 18 of Part I, there is good reason to believe that it has a metallic core surrounded by concentric layers of less and less dense material, with a veneer of granitic rocks at the surface. Such density stratifica-

tion resembles that of the slag in a furnace, where the molten materials have arranged themselves according to density. This is difficult to explain on the assumption that the Earth remained solid during slow growth by the infall of solid particles; it implies, rather, a molten stage.

Belief in a molten Earth is also confirmed by other lines of evidence; for example, the quantity of salt in the sea. Salt is produced in the weathering of primary rocks bearing sodium, and being highly soluble, is largely carried by streams to the sea, where it remains in solution. Throughout geologic history this transfer of salt to the sea has been going on, and still seawater is only about one-tenth saturated with respect to salt. Calculation shows, however, that all this salt could be derived from the weathering of a surface layer of average igneous rocks only half a mile deep over the Earth. If weathering and erosion had taken place during the slow growth of the outer 2000 miles or so of the Earth's crust, the oceans should be saturated with salt. Unless there is some unsuspected agent removing salt from the sea, the Earth must have been full-grown before erosion began; this would be the case if it were originally molten. In addition, there are direct implications that the Moon and the planet Mercury were molten until tidal friction had slowed down their rotation to agree with their periods of revolution, so that Mercury keeps one face always toward the Sun, just as the Moon keeps one face toward the Earth. If these bodies were molten, other members of the system probably were, likewise.

Furthermore, it is doubtful that planetesimals, once formed, could persist for long. Their mutual collisions would have served to scatter them into dust or reduce them to gas, and if so, the material ejected from the Sun would eventually have been largely dissipated into a gaseous condition. In any event, the major planets must have developed as gaseous rather than solid bodies, for their low densities indicate that they are still largely gaseous.

Finally, there is no longer reason to believe that the ejected material would have left the Sun in the form of "bolts." The solar prominences are now known to consist of particles of atomic size driven out by the radiation pressure of light, a force utterly ineffective against a large mass such as the postulated bolts.

The Gaseous Hypothesis

In view of the serious objections to the Planetesimal Hypothesis, two British scientists, Sir James Jeans, astronomer, and Harold Jef-

freys, geophysicist, developed the hypothesis that the disrupted material left the Sun as a steady stream of incandescent gas. They deny the importance of internal explosions in the Sun, pointing to its even, circular periphery and noting that the solar prominences are inconsequential.

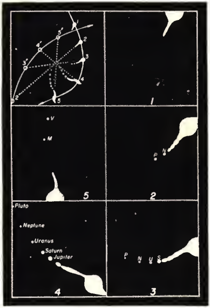


FIG. 49. Idealized diagram to illustrate the theory of tidal disruption and the evolution of a gaseous filament into planets. The upper left panel shows the courses of the ancestral sun (*white*) and a passing star (*circles*) during a near collision. Five stages here indicated in the evolution of the Solar System are shown on a larger scale in panels 1 to 5. No attempt has been made to show the true scale of sizes or distances. The passing star may have been larger than the sun. It may also have suffered disruption and may have developed a system of planets of its own.

Formation of a Gaseous Filament. On this assumption the tidal bulges rose to a critical height as Sun and star approached; then, the solar gases gushed forth in a steady stream from the advancing tidal bulge (possibly also from the opposite bulge). This continued until the disturbing star had passed and the tidal forces began to subside. Meanwhile the stream of hot gas had been drawn out to a distance of many millions of miles as a slender gaseous *filament* of cosmic proportions.

Since Sun and star were constantly changing relative positions (Fig. 49, upper left panel), the filament was not only drawn out from the Sun but also was given a backward pull which set the entire system in rotation in the plane of encounter.

Segmentation of the Filament into Planets. Such a slender stream of gas would be as unstable as a stream of water from a garden hose and, like the latter, would tend to break into segments and contract into spheres. Figure 49 is an attempt to visualize the evolution of the partially disrupted Sun into our Solar System. The upper left panel shows the course of the ancestral Sun (*white*) during near collision with the passing star (*circles*). Because of mutual attraction, both Sun and star were deflected from their normal courses as they approached and curved about a common center of gravity. As the

Sun occupied positions 1, 2, 3, 4, and 5, in turn, the passing star was in positions 1′ (beyond the panel), 2′, 3′, 4′, and 5′, respectively. The conditions in the Sun at these five stages are shown on a larger scale in panels 1 to 5. The filament had begun to form in position 1, and was more elongated in position 2. By this time, however, the outer part had begun to break into segments that were to form the outermost planets, Pluto and Neptune. The outflowing filament continued to shed segments at its free end; in position 3, four of the planets were born, and in position 4, the five outer planets had appeared and another segment was forming. Before it had reached position 5, ten segments had been freed, the disturbing star had passed, the tidal force was subsiding, and the remaining filament was falling back into the Sun.

Meanwhile the ten segments had been pulled far out from the Sun and drawn toward the receding star so that, as its attraction died down, they did not fall directly back toward the Sun but swung in elliptical orbits about it.

Many features of the Solar System find an explanation in the assumption that the filament varied systematically in size and constitution from outer to inner end. The outer part, it seems clear, consisted of the lighter gaseous material drawn from the surface of the Sun; but as the star approached and tidal forces steadily increased, heavier materials were drawn up from deeper within the Sun and, furthermore, the stream of gas increased to a maximum girth as the star passed and then became thinner as the tidal forces declined.

This accounts satisfactorily for the size of Jupiter and the regular decrease in size as we pass outward through Saturn, Uranus, and Neptune. It also accounts, in part, for the small size of the inner planets. Here, however, another factor came into play.

When first broken from the filament, each segment was made of intensely hot gas tending to spread into space. Only the internal gravity in each could counteract rapid leakage of the lighter gases. There is a critical size above which this internal force would hold the gases, even in a heated condition, and this can be shown to lie between the mass of Jupiter and that of the Earth. Hence in the early development of the system the great segments lost almost nothing, while the small ones suffered great wastage of their lighter constituents. The attraction of the Sun undoubtedly helped also to rob the nearer planets of their escaping gases. As a result, the minor planets, made of the small segments formed from the tapering inner end of the filament, suffered great wastage, were unduly reduced in size, and attained

a specific gravity far above the average for the planets in the system. Mars, especially, seems to have suffered because of its nearness to Jupiter. Thus, the differences in density among the planets find a rational explanation.

During the encounter the filament and its segments were not only drawn out from the Sun, but the segments were also drawn progressively farther apart. This is a natural consequence of the law of gravitation. The attraction between two bodies varies inversely as the square of their distance. Therefore, as each segment left the Sun and came nearer the disturbing star, its motion was accelerated. The first forward segment thus reached the greatest distance from the Sun not merely because it started first, but also because, being nearest to the passing star, it had traveled faster than any other segment during the encounter. This appears to account for the fact that the planets are spaced so that each is approximately twice as far as the next nearest from the Sun.

Development of Circular Orbits. After the breaking of the filament and the recession of the passing star, each segment was allowed to fall back toward the Sun. Its original course must therefore have been elliptical, and the present nearly circular orbits of the planets require explanation. For this, Jeans and Jeffreys invoke the interference of the gases that leaked away from the filament, formed a vast atmosphere pervading the whole system, and rotated as a unit with the Sun. For a time this gaseous medium may have been relatively dense, even though it has since condensed about the Sun (and perhaps the major planets) and has thus disappeared. Such a gaseous envelope would have formed a "resisting medium" through which the planets had to plow their way in their elliptical flights about the Sun. It can be shown that the effect of this would have been to retard the planets in their outward flight and speed them on their return toward the Sun, thus gradually rounding their elliptical orbits into circles.

Formation of the Satellites. Upon the first revolution, each segment must have passed relatively near the Sun. If so, it suffered tidal strains precisely like those induced in the Sun by the passing star. The small, inner planets, having lost their lighter gases and approached a liquid condition, escaped without catastrophe, but the large segments, still completely gaseous, suffered tidal disruption, a gaseous filament being drawn from each in turn as it passed the Sun. Segmentation of these filaments produced the satellite systems of Jupiter, Saturn, Uranus, and Neptune.

The Moon, on the contrary, presents a special case. It is relatively a giant among the satellites and was obviously formed in a different way. Calculations have shown that if a liquid or a semiliquid body were disrupted by tidal strains, the result would be a gradual fission into two instead of the ejection of a filament. Apparently Earth had reached just this critical stage at the time of its first journey past the Sun, and our Moon was separated from it in this way, gradually receding to its present distance.

The irregularity of certain of the satellites is attributed to their capture by one planet from another during the early stages of development of the system, while the orbits were still decidedly elliptical and the planets occasionally came nearer to each other than they do now. In this way, perhaps, the retrograde satellites of Jupiter and Saturn may be explained.

The Primordial Earth. According to the hypothesis just sketched, the Earth was at first gaseous and self-luminous, gradually cooling through a molten stage to a solid. It was thus full-grown at birth and molten until just before the beginning of geologic time. Nutting [3] has clearly outlined the sequel which followed.

If the original temperature exceeded 5000° Absolute, all the elements were above their critical temperatures and must have remained gaseous and uncombined. But when the Earth had cooled to about 4000° A., iron and silica could condense to form a liquid core, and a few oxides and carbides could form, floating, like cream, at the surface. At 3000° A. these first-formed compounds could begin to crystallize into the first solids on the Earth.

Meanwhile nearly all the oxygen, as well as many other elements in lesser amounts, remained as free gases to form a vast atmosphere probably a thousand miles thick and exerting a pressure of more than 30 tons per square inch on the liquid core.

When the temperature had dropped to about 2200° A., however, a profound change began, for then oxygen could combine with other elements to form silica and silicates. As convection currents in the liquid core brought ever-fresh supplies of material to the surface, oxidation proceeded on a colossal scale until the molten silicates were formed, from which the rocks of the Earth's surface would later solidify. Meanwhile, as the oxygen was thus used up, the atmospheric pressure decreased. When, later, the molten Earth began to solidify, convection currents could no longer reach the surface, and oxidation of the materials in the core ceased. Whether this occurred in time to prevent the total depletion of the oxygen from the primal atmosphere

is uncertain. If it did, the atmosphere has always had abundant free oxygen; if not, the present oxygen has been supplied by the photosynthesis of living plants during geologic time.

Another profound change occurred when the temperature had finally dropped to 374° C., for this is the critical point above which water will vaporize in spite of any pressure. Up to this time all the water upon the Earth was held in the atmosphere; now it could begin to condense.* As the temperature dropped lower, rain descended in torrents beyond human conception, thus initiating erosion and forming the oceans. Of course, the removal of vast quantities of water vapor from the air lowered both the atmospheric pressure and the boiling point, so that not all the water could condense at once; but probably 95 per cent of it had fallen by the time the temperature at the surface had dropped to 200° C.

Finally, solar heat began to play the principal part in warming the Earth through the now thin and broken canopy of cloud. For the first time sunlight attained the surface of the lithosphere, and the origin of life was possible.

With the condensation of the waters and the beginning of erosion we pass from the cosmic to the geologic history of the Earth.

Objections to the Gaseous Hypothesis. Critical analysis has already revealed shortcomings in this hypothesis, most of which are too technical for presentation here.

The first objection concerns the distribution of the *energy of motion* (the moment of momentum) in the Solar System. The Sun, for example, with more than 99 per cent of the mass in the entire system, possesses less than 3 per cent of the energy of motion, whereas Jupiter, with less than one-tenth of 1 per cent of the mass of the system, possesses nearly 60 per cent of the energy of motion. This would seem to imply that at the time of disruption nearly all the energy imparted by the passing star was given to the planets, with the lion's share going to Jupiter and but little to the Sun. Furthermore, there is great irregularity in the share of the energy possessed by the several planets. This peculiar distribution of the energy of motion among the members of the Solar System is a serious obstacle not explained by the Gaseous Hypothesis, and it applies with equal force to the Planetesimal Hypothesis. In an attempt to explain it, Russell (1935) suggested that at the time of near collision the Sun was a binary star with one

* This is far above the boiling point of water under present surface conditions, but the atmospheric pressure then probably exceeded 3700 pounds per square inch, and under such pressure the boiling point is 374° C.

large and one small component, and that the smaller one was disrupted to form the planets and their satellites. On this assumption, most of the energy of motion of the planets may have been inherited from the disrupted component. Although this offers a more rational explanation of the distribution of the energy of motion than any other hypothesis yet suggested, it encounters other obstacles and was finally considered by Russell to be unsatisfactory.

The origin of the satellites offers serious difficulties for the Gaseous Hypothesis, as well as for the Planetesimal Hypothesis; these are, unfortunately, too technical for brief treatment.

Indeed, there are numerous other obstacles, discussed by Russell in 1935 and too technical for treatment here, that make all present theories of the origin of the Solar System seem inadequate. Tidal disruption of an ancestral sun still appears to be the most probable starting point, but the development of the Solar System continues to offer unsolved problems.

At present the conclusions most plausible appear to be: (1) that the System is not eternal, but came into being more than two billion years ago through reorganization of pre-existing matter, (2) that Earth and the other members of the Solar System were genetically related in their origin, (3) that Earth and Moon passed through a molten stage, and (4) that Earth was essentially full-grown before geologic processes of erosion and sedimentation began on it.

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[3] *The Physical Chemistry of a Cooling Planet;* by P. G. Nutting. Journal of the Washington Academy of Sciences, Vol. 33, 1943, pp. 121–124.

Collateral Reading

Astronomy; by Robert H. Baker. 527 pages. Van Nostrand Co., New York. 3rd ed., 1938.

An up-to-date general textbook of astronomy.

The Two Solar Families; by T. C. Chamberlin. 311 pages. University of Chicago Press, 1930.

An extended account of the Planetesimal Hypothesis.

The Solar System and Its Origin; by Henry Norris Russell. 144 pages. The Macmillan Co., New York, 1935.

Reviews leading theories of the origin of the solar system and marshals objections to each of them.

The Universe around Us; by Sir James Jeans. 297 pages. Cambridge University Press. 4th ed., 1944.

Readable account of the structure of the atom, the nature of stars, the organization and origin of the solar system.

The Birth and Death of the Sun; by George Gamow. 238 pages. The Viking Press, New York, 1940.

Entertaining and stimulating.

Biography of the Earth; by George Gamow. 242 pages. The Viking Press, New York, 1941.

A sweeping and fascinating account, in large part devoted to pre-geologic history; suffering from a non-critical treatment of some strictly geological ideas.

Harvard Books on Astronomy, edited by Harlow Shapley and Bart J. Bok, are authoritative, up to date, and entertainingly written. The following volumes may be of special interest here:

Between the Planets; by Fletcher G. Watson. 222 pages. The Blakiston Co., Philadelphia, 1941.

An account of the planetoids, meteors, and meteorites.

Earth, Moon, and Planets; by Fred L. Whipple. 293 pages. The Blakiston Co., Philadelphia, 1941.

Galaxies; by Harlow Shapley. 229 pages. The Blakiston Co., Philadelphia, 1943.

An account of the Milky Way and other galaxies, including a discussion of the idea of an expanding universe.

The Dust Cloud Hypothesis; by Fred L. Whipple. Scientific American, Vol. 178, No. 5, May, 1948, pp. 34–45.

A popular account of the newest speculation on the origin of stars and of the solar system.

CHAPTER 6

THE CRYPTOZOIC EON: PRE-CAMBRIAN HISTORY OF THE EARTH

> "What seest thou else
> In the dark backward and abysm of time?"
> —*The Tempest,* Act 1, Scene 2.

The Ruins of Time. Earth's beginning was followed by long eras that are veiled in the shadows of antiquity. Enormous groups of ancient rocks, lying in tangled confusion below the Paleozoic, form an impressive record of those early times; but without fossils to date them, each is like a fragment of an unpaged manuscript that has been scattered and torn. With local exceptions they have been intensely deformed; in large part they have suffered strong metamorphism; and only remnants have escaped erosion or burial by younger formations.

In this respect the early history of the Earth is beset with difficulties like those encountered in the study of early man. Back of the historic past stretch the millennia of forgotten civilizations known to us only through the ruins they have left. Silent abodes of the cliff dwellers, like scattered implements of Paleolithic man, document chapters in the early history of civilization no less real because they are not yet fully understood. They are disconnected fragments of a record that grows clearer with each new discovery.

In this spirit we must approach the early history of the Earth. For these remote ages we have only fragments of a record. Eventually, study of radioactive minerals may give us dates so that we can fit most of the pieces into their places in the time scale, but as yet it is uncertain even how many eras of time they represent. Thus far two eras, the *Archeozoic* and *Proterozoic,* are commonly recognized, but we may find eventually that several eras preceded the Cambrian.

Distribution of Pre-Cambrian Rocks. Pre-Cambrian rocks are presumably world wide in extent, but in four-fifths of the land surface they are buried by younger formations. Exposed areas (indicated in Fig. 50) are of two sorts: (1) the cores of mountain ranges where great uplift and deep erosion have laid them bare, and (2)

the so-called *shields*,* which are stable areas that since Pre-Cambrian time have never been deeply covered.

The greatest of these stable areas is the *Canadian Shield*, which centers in Hudson Bay, stretches southward to the Great Lakes, westward to the plains of Alberta, and eastward to include Greenland, embracing more than half of Canada. As indicated in Fig. 50, each of the continents has at least one of these ancient shields. In

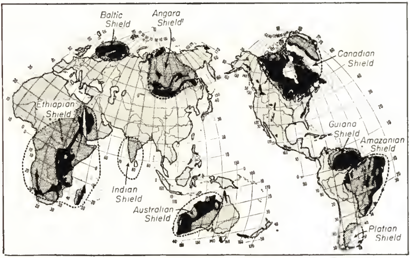

FIG. 50. Map showing the areas of outcrop of Pre-Cambrian rocks (*black*). The several *shields* are heavily stippled and are named. Base map by courtesy of the American Museum of Natural History.

general, they were sites of great activity during Pre-Cambrian time, then became stable, and subsequently have stoutly resisted deformation and, through prolonged erosion, have become great interior plains.

Nature of the Pre-Cambrian Record

The Pre-Cambrian history of the Earth as a whole can be sketched only in the most general terms; the difficulties of correlation between widely separated regions limit our study for the most part to local facets of the record. As an archeologist must depend upon the records of widely scattered sites in the study of prehistoric man, so we must

* The name *shield* was suggested by the fact that the surface of each of these areas of ancient rocks arches up in gentle convexity like the surface of a medieval shield.

choose a few typical regions to illustrate the nature of the Pre-Cambrian rocks and the problems they present.

The Grand Canyon Section

One of the clearest and grandest of the exposures of Pre-Cambrian rocks may be seen in the Grand Canyon of the Colorado. Here Lower Cambrian strata, still essentially horizontal and undisturbed, overlie, with profound unconformity, two great systems † of formations.

The older of these, the Vishnu schist, is well exposed in the Inner Gorge (Fig. 51). It is a complex of mica, quartz, and hornblende schists, intruded locally by granite and shot through with a complex of pegmatite dikes. Planes of foliation stand nearly vertical except where the schists are gnarled and crumpled. Quartzites occur at many places in the complex and, while for the most part these are thoroughly recrystallized, some preserve evidence of stratification and even of cross-bedding, thus betraying a definite sedimentary origin. It is inferred that most of the intervening schists also were originally sedimentary rocks, probably fine muddy sandstones and shales.[1] If so, the Vishnu schists represent a sedimentary series of very great but undetermined thickness that has been intensely metamorphosed, probably at great depth. It is believed to be, in part at least, equivalent to the "Older Pre-Cambrian" rocks that are exposed in the ranges of south central Arizona which, although strongly deformed, are clearly sedimentary and have a thickness of some 15,000 feet.[2]

Unconformably resting on these old schists is a great thickness of sedimentary formations aptly named the *Grand Canyon system.* Formations of this system once covered the whole region in regular, horizontal beds, but before Cambrian time they were reduced to remnants in several downfaulted blocks. Walls of the Canyon west of the mouth of Little Colorado River show a simple conformable succession of these strata exceeding two miles in thickness (Fig. 52).

The Grand Canyon system is essentially unmetamorphosed, thus contrasting in the most striking manner with the underlying schists, which must be vastly older. The system begins with a basal con-

† In the Pre-Cambrian, as in the later rocks, the largest units are called systems, but in the absence of adequate fossils, world-wide correlation is impossible, and local systems are recognized in different regions. In this respect the Pre-Cambrian systems are not comparable to those of later times.

glomerate resting on a peneplaned surface of the Vishnu schists. Following this come limestone and then limy shale and sandy shale and quartzites. Near the middle there are flows of basic lava. The limestones, and probably a large part of the shales and quartzites, were deposited in shallow marine water, but parts of the sandy shale and sandstone are bright red and are so commonly mud cracked as to suggest deposition on a broad floodplain. The region was probably part of a great delta plain in which submarine and subaerial deposition alternated. And since these strata were formed near sealevel, the region obviously subsided slowly and to the extent of many thousands of feet while deposition was in progress.

Spence Air Photos.

FIG. 51. Pre-Cambrian rocks of the Grand Canyon, looking east from a point about 10 miles due east of El Tovar Hotel. In the foreground is the inner gorge carved in the Vishnu schist (*V*); here the Cambrian (*C*) rests directly upon the schist, but in the middle distance the Grand Canyon strata (*GC*) appear as a wedge, thickening and dipping away from the observer. A dotted line follows the unconformity between the Vishnu schist and the Grand Canyon system, and a white line follows the angular unconformity at the base of the Cambrian.

Some of the limy beds include characteristic deposits of lime-secreting algæ. These are one of the lowest forms of plant life (blue-green algæ), consisting of tufts of microscopic filaments, each a single chain of cells. In using the carbon dioxide from the surrounding water, they involuntarily precipitate calcium carbonate which settles over the colony, film upon film, to build up massive or hemispherical deposits with a characteristic laminated structure (Figs. 71, 72). Such plants have survived from Pre-Cambrian time to the present, persisting in this lime-secreting habit; they are therefore commonly known as the *calcareous algæ*. Sponge spicules also have been identified from these rocks. Thus one of the lowliest forms of plants, and one of the most primitive groups of animal life, are recorded here; but the Grand Canyon beds are for the most part destitute of fossils.

SPENCE AIR PHOTOS.

Fig. 52. Aerial view of the north wall of the Grand Canyon, looking north from a point 2 or 3 miles west of the mouth of Little Colorado River. A broken white line follows the base of the Cambrian system, which is approximately horizontal. Beneath it, dipping to the right, are beds of the Grand Canyon system. The arrows a plus b plus c span the thickness of the Grand Canyon strata here exposed.

The Pre-Cambrian history of this part of North America may now be summarized with the aid of the block diagrams shown in Fig. 53. Block *A* represents the earliest stage we know, when the rocks deep in the roots of a primeval mountain system had been folded and recrystallized to form the Vishnu schist. The surface relief is purely symbolic and is without direct evidence, but the character of the schists clearly indicates that we are dealing with the roots of mountains. The masses of bedded quartzite that locally plunged down through them were once horizontal layers of sand; they now betray vestiges of mountain folds otherwise obliterated by the intense pressure and heat to which they were subjected while deep within the zone of flow. The granitic intrusions were probably formed at this time. This intense deformation extended far beyond the Grand Canyon re-

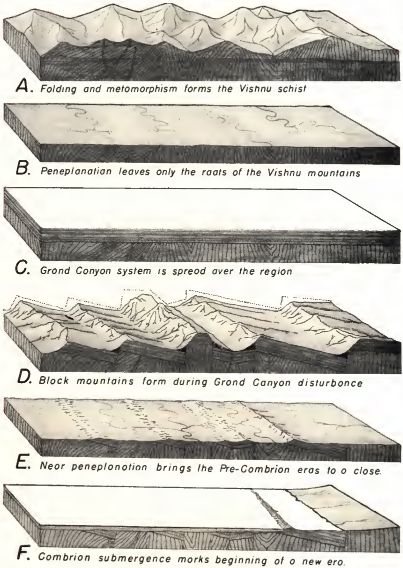

Fig. 53. Six stages in the Pre-Cambrian history of the Grand Canyon region. The view is northward, and the sections represent an east-west distance of about 15 miles. The solid black shading in block D represents alluvium about the flanks of the Grand Canyon ranges. The great wedge of Grand Canyon formations near the right end of block F is pictured in Fig. 52.

gion. In south central Arizona it produced intense folding and imbricate thrusting, accompanied by granitic intrusion on a large scale. For that area the orogeny has been named the *Mazatzal revolution.*[2]

Whatever the nature and height of those ancient mountains, they were eventually worn down to a remarkably flat peneplane (block *B*). The region then began slowly to subside, probably as part of a vast geosyncline that extended northward through Montana (Fig. 54), and the Grand Canyon deposits began to accumulate, layer upon layer, until they had a thickness of more than 12,000 feet (block *C*). During deposition there was a relatively short time when volcanic activity broke out in the form of basic lava flows.

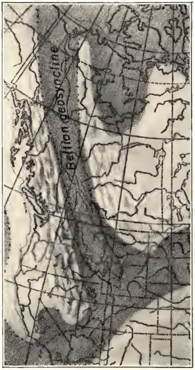

FIG. 54. The Beltian geosyncline, after C. L. and M. A. Fenton. The dotted lines mark the inferred limits of marine deposition.

Eventually the region was uplifted and, with but slight folding, was broken by great normal faults that gave rise to a system of block mountains much like those which now form the Basin and Range province east of the Sierra Nevada. This episode of mountain making has been named the *Grand Canyon disturbance.* Of course, these blocks suffered erosion as they rose, so that their height at any particular time can not be determined. However, remnants of a dozen or so great blocks are still preserved, and their bounding faults are clearly evident, so that the size and orientation of the ranges can be plotted; and if we project the dip of the beds in portions of the fault blocks still extant, the restored edges reach elevations more than 2 miles above their present surface (block *D*).

In time these mountains were destroyed and the region was again almost peneplaned (block *E*) before the early Cambrian seas spread over it to mark the beginning of a new era (block *F*).

There are, then, two profound unconformities in this section, each representing an immense lost interval during which the entire region was slowly reduced by erosion from bold mountainous relief to a peneplane. It is probable that the hiatus above the Vishnu schist (blocks A and B of Fig. 53) represents as much time as all the post-Cambrian rocks together.

Rocky Mountain Region

In western Montana, Idaho, and British Columbia, Pre-Cambrian formations are thick and widely exposed. Here, as elsewhere in the Rocky Mountain region, they fall readily into two groups separated by a profound unconformity, one representing Early and the other Late Pre-Cambrian time.

PHOTO BY HILEMAN, COURTESY OF GREAT NORTHERN RAILWAY.

Fig. 55. The "Garden Wall" overlooking Iceberg Lake in Glacier National Park. This towering cliff exposes about 2000 feet of the Siyeh formation of the Beltian series. The Collenia bed is formed of calcareous algæ.

Early Pre-Cambrian. The Early Pre-Cambrian formations are intensely deformed and commonly are strongly metamorphosed. They vary in character from area to area and may represent widely different periods of time. Unfortunately there is no adequate basis for correlating the many outcrops, beyond the fact that all are older than a regional hiatus of great magnitude. As a result, only local formation or group names have been used for these Early Pre-Cambrian rocks.

The Beltian System. The Late Pre-Cambrian rocks of this region form a natural unit known as the *Beltian system,* so named for exposures in the Little Belt and Big Belt Mountains east of Helena, Montana. These are sedimentary formations similar to those of the Grand Canyon system farther south, and are believed to have formed in the same geosyncline (Fig. 54). Exposures are scattered over a belt some 300 miles wide from east to west, and sections range in thickness from a minimum of about 12,000 feet in the east to more than 35,000 feet in the west. Exceptionally fine exposures may be seen in Glacier National Park at the northwest corner of Montana, where a thickness of 25,530 feet has been measured (Fig. 55).

This system is divisible into a number of apparently conformable formations, some of which are of regional extent.

Where typically developed in Little Belt Mountains, eight formations are recognized, five of which are shales, two limestones, and one (the lowermost) a mixture of sandstone and quartzite. The shales are in part sandy, and generally are so indurated as to be called argillites. The predominant color is gray, but red shales some 1500 feet thick occur near the middle, and others appear higher up. The limestones are notable because of their exceptional thickness, the lower one measuring about 2000 feet and the upper 4000 feet. These are predominantly gray in color and vary from thin- to thick-bedded and from argillaceous to pure.

As the system thickens toward the west, the limestones become more impure and eventually are replaced by shale and sandy shale; the chief source of these sediments therefore obviously lay to the west of the geosyncline.

The gray shales of this region commonly show oscillation ripples, indicating deposition under standing water; but some horizons, notably in the red zones, display abundant mud cracks, proving that the mud flats were at times exposed to the air long enough to dry up. Cross-lamination in the more sandy beds and other evidences of shallow

deposition are common. Reeflike deposits of calcareous algæ are locally conspicuous in the limestones and in some of the gray shales. For the most part the Beltian formations were clearly deposited on the floor of a shallow sea that occupied a broad geosyncline, but the conspicuously mud-cracked shales were probably formed over low floodplains during periods when the surface had been built up a little above sealevel.

In Glacier National Park, basic lavas, locally interbedded with the sedimentary strata, are widely distributed and occur at several different horizons.[3] They display amygdaloidal and pillow-lava structures and other evidences that they were contemporaneous flows on the sea floor. Most of these are thin, only locally ranging up to 300 feet or more in thickness.

Cambrian strata directly overlie the Beltian in many places and generally appear to be parallel to the latter, as though no uplift or disturbance had occurred in this region at the end of Pre-Cambrian time. Regional study shows, however, that the Cambrian system is transgressive on successive formations of the Beltian system, and in

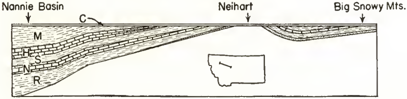

FIG. 56. Idealized and restored section of the Beltian system in Montana, showing its unconformable relation to the Cambrian (*C*). The section runs from Nannie Basin in the Swan Range to the Big Snowy Mountains, a distance of 200 miles. The vertical scale is 4 times the horizontal. In the Nannie Basin the thickness of the Beltian rocks exceeds 10 miles. The unconformity is due to warping, regional uplift, and long erosion before the start of Cambrian deposition. *R*, Ravalli redbeds; *N*, Newland limestone; *M*, Missoula sandstone and shale. After Charles F. Deiss.

places (for example, Neihart in the Little Belt Mountains) rests directly on the Early Pre-Cambrian metamorphics (Fig. 56). It is therefore evident that before Cambrian time the Beltian system had been gently warped and uplifted to an amount that reached several thousands of feet in some areas, and that the region was then peneplaned before the beginning of Cambrian deposition. This uplift probably took place while the Grand Canyon disturbance was under way farther south.

Canadian Shield

General Features. This is at once the largest and the most intensively studied area of Pre-Cambrian rocks in the world. First to

attack it was Sir William Logan (Fig. 57), who in 1842 undertook to organize the Geological Survey of Canada. Almost at once he turned his attention to the areas of ancient rocks along the north shore of the Great Lakes, influenced, no doubt, by rumors of mineral wealth brought back by early explorers. Subsequent discoveries of fabulous deposits of iron and copper and nickel and silver and gold have stimulated continuous exploration and study of these rocks for more than a hundred years. Even so, the region is so huge and so complex in its geology that it still abounds in unsolved problems.

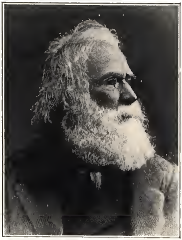

Fig. 57. Sir William Logan (1798-1875), father of Pre-Cambrian geology.

A large part of the two million square miles of the Canadian Shield is formed of granite and gneiss (Figs. 58, 59); the rest consists of irregular and relatively small patches of sedimentary and volcanic formations resting on granite. When first studied, this granite was supposed to be part of the "original crust" of the once molten Earth and to have been the floor upon which the sedimentary and volcanic formations were laid down; but critical study later revealed that in many places these surface rocks were intruded by the granite (Figs. 60, 63) and are intensely metamorphosed near the contact. Obviously, in such places the sedimentary and volcanic rocks are remnants of more widespread formations that once covered the region and formed a roof into which the granite was intruded. With the advance of regional study, it has become clear that this relation is general; so far as we now know, the original crust has been engulfed everywhere by the rising magmas, or so completely re-fused as to be unrecognizable, and the oldest sedimentary rocks in the Shield "float like islands in a sea of granite."

Granites. This granite is not the product of one intrusion but of many, distributed over an immense span of time—probably more than 1000 million years. It is a complex of batholiths, individually only tens or scores of miles across, and it is possible that no vast subsurface mass was all fluid at once. That there are batholiths of widely dif-

ferent ages, intruded one into another, is clearly shown by (1) local relations to the sedimentary formations described below (p. 104) and (2) the ages determined by radioactive minerals. For example, lead-uranium ratios indicate that the granite about Parry Sound, Ontario, was intruded 780 million years ago; the age of that in Haliburton

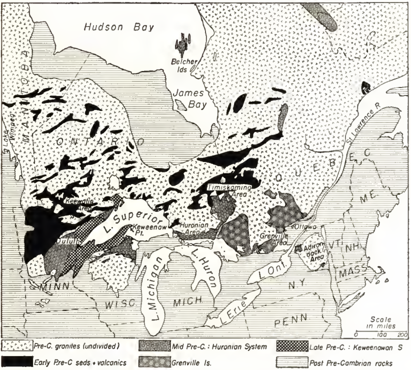

FIG. 58. Outcrop map of the southern part of the Canadian Shield and adjacent parts of the United States. Adapted from the Geologic Map of North America compiled by George W. Stose and published by the Geological Society of America, 1946.

County, Ontario, is 1050 million years; of that about Rice Lake in eastern Manitoba, 2000 million years.

Early Pre-Cambrian History. Correlation of the scattered areas of sedimentary and volcanic rocks in the Canadian Shield presents almost insuperable difficulties, some of which will disappear with more field work, whereas others may never be solved. Meanwhile we shall examine only enough local details to illustrate the general history of the region, avoiding, so far as possible, highly controversial problems. For this purpose a simple subdivision into *Early Pre-Cam-*

M. E. WILSON, GEOLOGICAL SURVEY OF CANADA.

Fig. 59. Laurentian gneiss, Grenville Township, Quebec. The dark layers are rich in pyroxene. The foliation dips steeply to the right.

brian, *Middle Pre-Cambrian*, and *Late Pre-Cambrian* will be useful.

Early Pre-Cambrian formations (solid black in Fig. 58) are the most widely distributed, but they occur in relatively small and extremely irregular patches. They are commonly recognized as being *Early* Pre-Cambrian only because they are overlapped with profound unconformity by younger rocks of Middle or Late Pre-Cambrian age, and because they are intensely deformed and as a rule strongly metamorphosed. In these respects they resemble the Early Pre-Cambrian of the West, and, like the latter, probably represent a great span of geologic time.

One of the most studied examples is the *Keewatin area* (*Keewā'tin*) along the Canadian border west of Lake Superior. Here the *Keewatin series* was named to include a complex of ancient lava flows and interbedded sedimentary rocks that reach the impressive thickness of 20,000 feet. Although strongly deformed and to a large extent altered to greenstone schists, many of the lavas are recognizably amygdaloidal, and they commonly display pillow-lava structures; hence it is clear that they welled up quietly and spread to form a layered deposit like the modern Columbia Plateau of Oregon and Washington. Locally there were explosive volcanoes, as at Michipicoten Bay, where the *Wawa tuff* is 11,000 feet thick.

The flows were interbedded in places with sediments that accumulated during intervals between eruptions. These locally attain con-

siderable importance, as in the Vermilion Range of Minnesota, where the upper lavas interfinger with the iron-bearing Soudan formation, which is about 1500 feet thick.

In the Rainy Lakes district there is a comparable mass of sedimentary rocks beneath the lavas. Some geologists regard this as a distinct series older than the Keewatin, but it is now commonly considered only a basal formation of that series.

The original extent of the Keewatin series is highly problematical. Keewatin rocks are recognized chiefly by the predominance of basic lava flows and by local structural relations. Contemporaneous deposits remote from the lava fields could not be identified by either of these criteria.

The Keewatin area was the scene of two discoveries of far-reaching implications in Pre-Cambrian geology. In 1883, when A. C. Lawson, just out of college, was sent to study this area, the rock now called granite was supposed to be part of the "original crust." Lawson soon found that the "fundamental gneiss," as it was called, actually intrudes the Keewatin series and has inclusions of greenstone that must have foundered into a rising magma; and he drew the obvious, but then astonishing, conclusion that the granite is younger than the surface rocks that rest upon it!

The second discovery came with his study of the *Knife Lake series* ‡ that occupies a number of synclinal basins in this area and rests with profound unconformity upon the Keewatin series (Fig. 60). It consists of several thousands of feet of slaty shales with a conspicuous basal conglomerate. In the latter, Lawson found boulders of the Laurentian granite, that is, the granite which intrudes the Keewatin series. This, of course, merely confirmed the structural evidence that the Knife Lake is much younger than the Keewatin series (since the granite, being plutonic, could be exposed at the surface only after profound erosion). But Lawson also found that granite is intrusive into the Knife Lake series! Evidently, then, there are granites of two ages here, one much older and one younger than the Knife Lake slates. To the younger he gave the name *Algoman.*

The strong folding of the Knife Lake series and the intrusion of Algoman granite afford clear evidence of large-scale orogeny in this area, and regional study indicates that it involved much of the south-

‡ The name Seine River series was used for these rocks by Lawson, who regarded them as equivalent to the Huronian series. Canadian geologists now commonly regard them as older than the Huronian.[7] The name Seine River is still commonly used locally.

ern part of the Canadian Shield and was largely responsible for the strong deformation of the Early Pre-Cambrian rocks. This important orogeny has been named the *Algoman revolution.* It involved large regional uplift and was followed by a very long period of erosion that eventually resulted in peneplanation of the Canadian Shield, destroying most of the previously formed sedimentary record and leaving only the deeply downfolded synclinal basins isolated much as they are today (black areas in Fig. 58). This great hiatus forms the boundary between Early and Middle Pre-Cambrian time, that is, between the Archeozoic and Proterozoic eras in this region.

FIG. 60. Idealized vertical section showing structural relations of the Laurentian and Algoman granites to the Keewatin and the Knife Lake (= Seine River) systems. Note that the basal conglomerate of the Knife Lake system includes pebbles of the Laurentian granite, and that it is cut by the Algoman granite.

Each of the isolated areas of Early Pre-Cambrian rocks (black areas in Fig. 58) has a thick sedimentary record comparable to that of the Keewatin area, and in most of these, basic lavas are associated with the sediments. In each, the thickness of sediments is impressive; the predominant rocks are graywackes (that is, poorly sorted and incompletely weathered sediments of dark color); conglomerates are conspicuous and commonly thick; pure, well-sorted sands and calcareous rocks are almost lacking. Such deposits appear to have accumulated rapidly and relatively near their source. They are, in short, typical geosynclinal deposits, and the reason that limestone, shale, and clean sandstones are so rare, and that the sedimentary record is so much alike in all these areas, is probably that only the deepest geosynclinal remnants escaped the post-Algoman erosion.[4]

In the Keewatin areas two distinct periods of Early Pre-Cambrian history are certainly represented; but it is not possible to determine whether comparable series of formations in other, isolated areas correlate with the Keewatin or the Knife Lake series, or whether several different periods are represented. For this reason, local series names

are used in each area. A good example is the Timiskaming series, some 20,000 feet thick, which occupies a relatively large area between Lake Huron and James Bay. Some geologists believe that many of the areas of Early Pre-Cambrian rocks are contemporaneous with these, and that they together constitute a *Timiskaming system* lying between the Keewatin and the Huronian; but others seriously doubt that such correlations are yet feasible.

C. W. Knight, Ontario Bureau of Mines.

FIG. 61. Gowganda tillite near the base of the Cobalt series at Drummond mine, near Cobalt, Ontario. The large boulder at the right above is 30 inches in diameter.

Middle Pre-Cambrian. *The Huronian System.* Along the north shore of Lake Huron is a large area of nearly horizontal sedimentary rocks, far younger and generally less deformed than those described above, and having a thickness of about 12,000 feet. Logan called these the *Huronian system.*

Rocks of this system stretch away to the northeast in nearly continuous exposures as far as the Timiskaming area, and also crop out extensively both northwest and south of Lake Superior (Fig. 58). They are clearly the deposits of a geosyncline that formed across the Great Lakes region after the long post-Algoman erosion had reduced it to a perfect peneplane.

As now understood, the Huronian system includes 15,000 to 20,000 feet of beds and is divisible into three series. In its type area only the *Lower* and *Middle Huronian* are present, the *Upper* appearing in the Lake Superior region.

North of Lake Huron the system consists largely of coarse detrital sediments—quartzites and conglomerates, chiefly—with only lesser amounts of graywacke and only a few beds of limestone. In the Lake Superior region it is generally finer of grain, includes much dark shale, and at several different horizons carries the beds of cherty iron carbonate and iron silicate from which the enormously important iron ores of this region have been formed.[5]

Royal Ontario Museum.

FIG. 62. Striated boulder from the Gowganda tillite at Cobalt, Ontario. About $\frac{1}{3}$ natural diameter.

The black slaty shales so common in the Huronian of the Lake Superior region owe their color to disseminated carbon, the residue of buried organic matter. Since no recognizable fossils have been found in the shales, the organisms were probably minute and soft-bodied; but the very large amount of carbon represented can mean only that life of a low order was abundant.

Glacial Deposits. Particular interest attaches to the Gowganda tillite (Fig. 61), widely distributed at the base of the Middle Huronian, which is clearly a glacial deposit, including striated and faceted boulders as much as 10 feet across (Fig. 62). In two places a grooved and striated glacial floor has been discovered beneath it. Patches of the tillite, locally as much as 500 or 600 feet thick, have been identified over an area nearly 1000 miles from west to east, indicating a continental ice cap of large proportions over at least the southern part of the Canadian Shield during Middle Huronian time.[6]

The Grenville Series. In his early work in the region between Montreal and Ottawa, Logan recognized a great complex of gneissic rocks associated with masses of intensely metamorphosed sediments, largely limestones. For this complex, which he considered older than the Huronian, he used the name "Laurentian series" (after the Laurentide Mountains along the north side of the St. Lawrence Valley).

Within this complex he distinguished a large and very thick belt of limestone striking across Grenville County, and this he referred to as the "limestone of Grenville." In later work in this province the name *Laurentian* came to be restricted to the granitoid and gneissic rocks, and the term *Grenville series* was used to include the metamorphosed sedimentary rock.

The Grenville series has extensive outcrops in Grenville County, Quebec, and extends into the Adirondack region of New York. Scattered remnants indicate that it once covered an area of more than 100,000 square miles, and over most of this area it is more than half limestone. In a nearly continuous exposure along the Hastings road in Hastings County it was estimated to have a thickness of 94,000 feet, but later work has indicated that the beds are isoclinally folded and the actual thickness may not exceed 10,000 feet. Even so, the Grenville series is one of the largest masses of limestone in the whole

GEOLOGICAL SURVEY OF CANADA.

Fig. 63. Crumpled Grenville limestone (light) with injections of Laurentian gneiss (dark layers). Prescott County, Ontario. The break in the beds near the left margin is due to faulting.

Pre-Cambrian record, and stands in marked contrast to the other sedimentary rocks of the Canadian Shield, which are almost exclusively detrital. To be sure, the Grenville also contains considerable detrital material; in the Thousand Islands region along the north edge of the Adirondacks it appears as thick masses of cross-bedded pure quartzite.

The structure is extremely complex throughout the Grenville area. The beds dip steeply into synclinal basins between granite batholiths that are intrusive and in places show an intimate injection between beds of limestone (Fig. 63). In places also there is clear evidence that large masses of the Grenville foundered and were engulfed in the granite magma. The limestone is now largely altered to marble, and the detrital beds to schists. The latter include much interbedded graphite. On the west side of Lake George, for example, graphite beds ranging from 3 to 13 feet thick have been mined at Hague, New York.

The age of the Grenville series and its relation to other groups of sedimentary rocks in the Shield are at present moot questions. This series was long supposed to be Early Pre-Cambrian and probably contemporaneous with the Keewatin; then during the decade after 1925 it was suspected to be a strongly metamorphosed equivalent of the Huronian system. Since then the lead-uranium ratios have been determined for radioactive minerals in the granites that are intrusive into the Grenville rocks, and they indicate ages ranging from 985 to 1195 million years. It now appears probable that the original conception was correct and that the Grenville rocks belong to the Archeozoic era.[7]

Late Pre-Cambrian. *Keweenawan Lavas and Redbeds.* After Huronian deposition, the Great Lakes region was gently uplifted, with more or less warping but little folding. After an interval of erosion, fissure eruptions began on a grand scale, and flow after flow of basic lava welled out, building up an extensive basalt plateau like that of Keewatin time. The surfaces of successive flows are still rough and slaggy, and much of the lava, originally highly vesicular, is now amygdaloidal. The total volume of these Keweenawan lavas about Lake Superior has been estimated at 24,000 cubic miles. During this time there were also colossal intrusions of basic magma in the form of sills, such as that which bears the nickel ores at Sudbury and that of the Duluth gabbro underlying much of Lake Superior.

The lavas are interbedded with, and succeeded by, red sandstones and shales which reach an aggregate thickness of 15,000 feet or more.

These beds include conglomerates, sandstones, and shales, much of which represents the material eroded from the rough lava surfaces and deposited rapidly over the lowlands of a barren landscape. The sediments were also partly derived from the older granites, and in places they contain red jasper pebbles obviously derived from the Huronian iron formations. There is no evidence of marine deposition; on the contrary, the oxidized condition of the red sediments, like the cross-bedding of the sandstones and the extensive mud cracking of the shales, implies deposition on alluvial plains under seasonal rainfall.

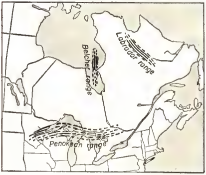

FIG. 64. Sketch map showing the distribution of Late Pre-Cambrian mountains in the Canadian Shield. After E. S. Moore.

The system is named for Keweenaw Peninsula on the southern shore of Lake Superior, where the amygdaloidal lavas and some of the interbedded conglomerates yield rich deposits of metallic copper.

The thickness of the Keweenawan system varies greatly, but in northern Michigan and Wisconsin may reach 50,000 feet, much more than half of which is made of lava flows.

Late Pre-Cambrian Orogeny. At least three great ranges of fold mountains were formed in the Canadian Shield during the latter part of Pre-Cambrian time (Fig. 64).[8] One of these, the *Penokean Range*, ran nearly east-west through the center of what is now the Great Lakes region. It is recorded by folds in the Huronian and Keweenawan rocks of Wisconsin, northern Michigan, and the north shore of Lake Huron and Georgian Bay. The width of the folded belt was at least 100 miles; it had a known length of 700 miles and probably extended still farther, since the folds show no decrease in intensity at either end of the exposed belt. The folds die out a short distance north of Lake Huron. It was this movement that folded the Huronian formations in the Iron Ranges of Wisconsin and Michigan, and the orogeny was named for the Penokee iron district (p. 115).

The *Belcher Range* ran nearly north-south along the eastern side of Hudson Bay, and in this region the Late Pre-Cambrian rocks are closely folded. The *Labrador Range* ran northwest-southeast across the heart of Ungava Peninsula.

There is still uncertainty as to the exact time of this deformation. In the Lake Superior region there was local deformation after Early Huronian, again after Middle Huronian, and yet again after Late Huronian deposition, and finally the entire Keweenawan system was involved in the deformation that created the Lake Superior structural basin. In connection with the post-Keweenawan movement granites were intruded along the axis of the Penokean range (in southern Minnesota, central Wisconsin, and northeast of Lake Huron). These granites have been identified as of Keweenawan age. "The principal folding of the Upper Huronian, as well as of the Middle and Lower Huronian, dates from this period." [9]

Recapitulation and Interpretation of the Record

Loss of the "Original Crust." It would be a matter of great interest if we could discover beneath the oldest sediments some portions of the original surface of the Earth, for they might reveal critical evidence bearing on the Earth's origin and might show whether it had been molten. In the regions thus far studied, however, we have seen no certain evidence of such primal rocks.

Colossal Igneous Activity. It stirs the imagination to contemplate the 2,000,000 square miles of granite gneiss that floors the Canadian Shield, and to realize that it all came into place as fluid magma, which congealed beneath a cover of older rocks now long since removed by erosion. The relatively small areas of sedimentary formations that lie infolded among these batholiths, as remnants of their former cover, convey the impression that during these primeval eras the crust of the Earth was repeatedly broken and largely engulfed in upwellings of molten material that dwarf all post-Cambrian igneous activity.

Of course, the intrusions were distributed over an immensely long period of time, and probably no vast subsurface area was all fluid at once, for the individual batholiths are only tens or scores of miles across. Moreover, we are impressed by the extent of the granitic rocks because profound erosion has stripped the batholiths of their roofs and laid bare horizons that were once several miles below the surface. Nevertheless, the regional extent of the folding and recrystallization of the old surface formations, and the vast stretches of granitic rocks, testify to the wide extent of the early igneous activity.

Great Diastrophism and Erosion. In each of the regions studied, two features of the record stand in antithesis one to the other. Great

sequences of conformable beds mark periods of quiet when the region for long ages subsided slowly as it received its sheets of bedded sediments. In some cases there are reasons to believe these sediments to be parts of great deltas or extensive floodplains, but in other instances the deposition was in shallow inland seas like Hudson Bay or the Baltic.

In contrast to these evidences of quiet and long-continued accumulation are great unconformities that imply periods of crustal unrest, mountain making, uplift, and destruction. It is clear, then, that long intervals of quiet have alternated with times of diastrophic change. In the Grand Canyon there are two profound unconformities. In the Lake Superior region there were at least three episodes of regional diastrophism and granitic intrusion, one following the Keewatin deposition, a much greater one (Algoman) succeeding the Early Pre-Cambrian, and the last (Penokean) coming late in the era. The second of these resulted in the strong folding of the Early Pre-Cambrian formations over a vast area along the southern part of the Canadian Shield, even in places which have escaped all subsequent deformation. It appears to have been the most widespread revolution experienced by the Shield and to have been followed by one of the longest intervals of erosion known anywhere. The Penokean disturbance, which came late in the Pre-Cambrian in this region, has already been described. It was followed by another of the great periods of erosion, one that is recognized in many parts of the world as the great break separating the rocks of Cambrian and later times from all that existed before.

Thus it is evident in all the areas of these ancient rocks that we have a far from complete record of Pre-Cambrian time.

Classification and Correlation of the Pre-Cambrian Rocks. In a single section like that of the Grand Canyon or the Belt Mountains, where different systems of rocks are actually superposed, it is not difficult to determine at least the right order of the sequence. But when we attempt to compare the Grand Canyon record with that of the Great Lakes or other distant areas, and to correlate formations and unconformities and episodes of igneous activity, grave difficulties stand in the way. If we wished to compare exposures a few miles apart, as in opposite walls of the Grand Canyon, we could recognize the same formation by (1) its lithologic appearance, (2) its position in a similar sequence of formations in the two exposures, (3) its relation to a regional unconformity or to intrusive igneous rocks, or (4) its degree of metamorphism.

These criteria can be applied with decreasing certainty over wider gaps many miles across, but when we attempt to correlate regions hundreds of miles apart, they are all unreliable. Rock formations change their characters greatly over such distances, sandstones giving way to shales or limestones, and vice versa. Even continental red-beds grade laterally into marine limestones, in some instances within a score of miles. Hence we can not correlate the red formations of the Grand Canyon system with those of the Keweenawan merely because they look alike. Moreover, mountain making is regional or local, and in consequence equivalent formations will be greatly disturbed in an orogenic belt and unaltered in a neutral area. Thus, for example, all the Paleozoic rocks are folded and in places strongly mashed in the Appalachian Mountains, though they lie nearly horizontal in the Allegheny Plateau shortly to the west of the disturbed belt. Hence the structural relations can not be trusted as a proof of equivalence over great gaps.

On the other hand, regional metamorphism, and regional unconformities that are planed down to plutonic rocks, serve as a basis of correlation over greater areas, since they are not local phenomena.

The greatest promise for the correct interregional correlations of these ancient, unfossiliferous formations lies in the study of their radioactive minerals. This type of investigation is as yet only begun, but its results are already of the highest interest, not alone because they have indicated a great age for some of the Pre-Cambrian rocks, but even more because, when the duration of the Pre-Cambrian eras is more surely known than at present, we shall be able to fit into its proper place any formation whose age is thus determined, regardless of its appearance or location.

Divisions of Pre-Cambrian Time. The scheme of classification now most widely used recognizes two Pre-Cambrian eras, the *Archeozoic* and the *Proterozoic*. When this subdivision came into vogue, it was generally believed that these were separated by a general and profound unconformity, and that the Archeozoic rocks were essentially igneous and largely in the form of gneisses and schists, whereas the Proterozoic were formed largely of sedimentary strata, more or less deformed and metamorphosed. However, modern studies around the Great Lakes have shown that the oldest systems there exposed include great masses of sedimentary rocks and the youngest Pre-Cambrian embraces extensive granitic batholiths, not to mention the Keweenawan lavas.

Furthermore, the actual dating of various Pre-Cambrian formations of the world by means of their radioactive minerals has shown that there are at least seven times of great orogeny and granitic intrusions in the Pre-Cambrian.[10] Yet only three or four of these have been recognized in any one continent. This alone suggests that our scheme is too simple and that the attempt to put all Pre-Cambrian formations into Archeozoic and Proterozoic is likely to be misleading. The tentative correlation which follows may, however, be useful as an attempt at the summation of our present understanding, but it is not to be considered final. Wavy lines are used to emphasize unconformable contacts.

Table of the Pre-Cambrian Subdivisions

Generalized Time Scale		Great Lakes Region	Western United States	
Proterozoic era	*Penokean orogeny, granitic intrusion and long erosion*		Grand Canyon system	Beltian system
Proterozoic era	Keweenawan time	Keweenawan volcanics and sedimentaries	Grand Canyon system	Beltian system
Proterozoic era	Huronian time	Animikie sedimentaries Cobalt sedimentaries Bruce sedimentaries	Grand Canyon system ?	Beltian system ?
Archeozoic era	*Algoman orogeny, granitic intrusion and long erosion*		Mazatzal revolution	
Archeozoic era	Knife Lake time	Timiskaming = Seine River	?	
Archeozoic era	*Laurentian orogeny, granitic intrusion and long erosion*		Vishnu schist	
Archeozoic era	Keewatin time	Soudan (etc.) sedimentaries Keewatin volcanics Coutchiching sedimentaries	Vishnu schist	

Mineral Wealth

The Pre-Cambrian rocks of the Canadian Shield have yielded iron, copper, nickel, silver, and gold beyond the dreams of Midas. The iron

is the sole sedimentary deposit, the other metals occurring in association with the igneous rocks. The exploitation of these metallic riches has played no small part in the industrial development of both the United States and Canada.

Iron. For many years, approximately 85 per cent of the iron produced annually in the United States has come from the Pre-Cambrian rocks of the Lake Superior district (Fig. 65). In the prewar year 1939 the output from this area amounted to 45,000,000 tons and was valued at $135,000,000. It rose to an all-time high of 91,000,000 tons in 1943 and was still nearly 75,000,000 tons in 1945.

The production is chiefly from the Middle Huronian rocks,[5] though some ore is mined also from the Lower Huronian and, in the Vermilion Range, from the Keewatin rocks. The ranges are more or less linear belts of outcrop of the dipping and folded iron-ore formations. That of Mesabi, which produces twice as much as all the others together, will serve for illustration (Fig. 66). It is part of the Middle

Fig. 65. Model of the Lake Superior region showing the distribution of the chief iron ranges. Photo of the model used by permission of the Director, U. S. Geological Survey.

Huronian series, which dips gently southeast. The iron formation consisted originally of cherty iron carbonate and greenalite (an iron silicate). This primary ore is not used, however, partly because it is only about 25 per cent iron, and partly because the silicate is too refractory to smelt. During the weathering of the outcrop in Pre-Cambrian time, however, the calcite and silica were partly carried away in solution, and the iron was oxidized and concentrated by descending solutions into large ore bodies that will yield over 50 per cent of iron. The rich ore bodies lie at the surface in the Mesabi Range and are mined by steam shovels in enormous open cuts (Fig. 67). In the Gogebic Range of Michigan, where similar iron formations

FIG. 66. Block diagram showing a section across the Mesabi Range at Hibbing, Minnesota. Length of section about 4½ miles. Adapted from Van Hise and Leith, U. S. Geological Survey.

are more strongly folded, the enrichment followed more definite conduits and reached to depths of about 3000 feet below the present surface, so that underground mining is necessary.

It is remarkable that some of the greatest iron mines of Europe are also in the Late Pre-Cambrian rocks (at Kiruna, Sweden), and that another of the greatest known iron deposits is in the Pre-Cambrian rocks of Brazil (Minas Geraes).

Copper. Native copper occurs in the lavas and conglomerates of Keweenaw Peninsula and was known and worked by the Indians long before the advent of white men. It forms amygdules in the scoriaceous lavas and not only serves as a cement between the pebbles in the conglomerate but also has partly replaced the pebbles themselves. As the copper is concentrated in certain beds and the series dips steeply to the northwest, the producing area is a belt only 3 to 6 miles wide, running for about 70 miles along the axis of the peninsula. The famous Calumet and Hecla mine is located on this belt. At its peak of production in 1916 this region alone produced 135,000 tons of copper, valued at $66,300,000. The yield had declined to 30,400 tons in 1945, but the grand total for the hundred years, 1845–1945, was over 4,800,000 tons, slightly more than one-seventh of the total production of the entire United States.

Nickel. Over 70 per cent of the world's nickel is now secured from the mining district of Sudbury, Ontario, where a great sill of gabbro, presumably of Keweenawan age, has a border of nickel-copper ore. The production from this small area increased from about 40,000 tons of nickel in 1933 to more than 105,000 tons in 1938; it reached a peak of 130,642 tons in 1943 and dropped back to about 110,000 tons in 1945.

Silver. Silver is found in many localities in the southern part of the Canadian Shield, generally in veins associated with basic intrusives of Keweenawan age. In some places the veins occur in Keewatin or Timiskaming rocks and in others in the Upper Huronian, but in all, the mineralization is closely restricted to the vicinity of the younger intrusives, which were the "ore-bringers."

At present the greatest production is from a small area (about 6 square miles) around Cobalt, Ontario, where native silver occurs in veins associated with a great sill of dolerite (Fig. 68). The richness of some of these veins is phenomenal, yields of 7000 ounces of silver per ton of ore being recorded. A number of lesser silver camps of similar nature are found within a radius of 75 miles west of Lake Timiskaming. Port Arthur, on the northwest shore of Lake Superior,

L. P. GALLAGHER.

Fig. 67. Open-cut mine in the Mesabi Range, Minnesota.

is another silver camp where both the Upper Huronian and the Keewatin rocks have been intruded by Keweenawan magmas.

Gold. There are likewise many occurrences of gold in the southern part of the Canadian Shield. The most spectacular production has been about Porcupine, a locality nearly 100 miles northwest of Lake Timiskaming. Although not discovered until 1912, it soon became one of the greatest gold camps in the world, and in the twelve years up to 1924 produced over $135,000,000 worth of gold. Its total output to 1947 has been nearly 20,000,000 ounces. The Hollinger mine is the chief producer of the area and one of the richest gold mines known. In 1938 its production of gold and silver together was valued at $15,000,000.

Arthur A. Cole.

Fig. 68. Silver vein at Kerr Lake mine, Cobalt, Ontario. The vein was exposed at the shore of a lake that has since been drained.

In the Porcupine district the gold occurs chiefly in the metallic form and in veins associated with granitic intrusions (syenite porphyry) in the Keewatin lavas and Timiskaming sedimentaries. As these ore-bringing intrusives are unconformably overlain by Middle Huronian strata, they are considered to be genetically related to the Algoman granite. In recent years the Kirkland Lake district has surpassed the Porcupine. These and other districts in the Canadian Shield have made Canada forge ahead in gold production to third rank among the countries of the world. The leading country in the production of gold is the Union of South Africa, and there also the metal comes from Pre-Cambrian rocks.

Since all these valuable metals—gold, silver, copper, nickel, and cobalt—are in veins associated with intrusives, it is clear that the great igneous activity of Pre-Cambrian time in this region has a very direct human and economic interest. In the single prewar year of 1938 these deposits in Canada yielded about $250,000,000 in mineral wealth.

After the close of the Keweenawan epoch no important ore deposits, so far as is known, were formed within or near the Canadian Shield.

The upsurges of magma during this vast Late Pre-Cambrian upwelling "seem to have exhausted the treasure-house" (Coleman).

Radium. One of the greatest known sources of radium was discovered in 1930 at La Bine Point on Great Bear Lake, northwest Canada, where pitchblende ores yield silver, uranium, and radium. In 1937 this deposit yielded $850,000 worth of silver and radium, and a vast reserve is now blocked out. It is one of the world's rich sources of uranium for subatomic energy. The ore occurs in deformed sedimentary and volcanic rocks that have been intruded by Pre-Cambrian granite.

Pre-Cambrian Rocks of Other Continents

Scandinavia. Much of Scandinavia is made up of Pre-Cambrian formations, which have long been the subject of study. After a life devoted to the interpretation of these rocks, Sederholm, the distinguished geologist of Finland, concludes that at least four great cycles of Pre-Cambrian sedimentation occurred in these northern lands of the Baltic Shield, and that each of them was separated from the next by a period of mountain folding and a long interval of erosion.[10]

Australia. Pre-Cambrian rocks form the surface of nearly one-third of the continent of Australia, chiefly in the central and western parts (Fig. 50), where they reach a vast thickness and rival in complexity those of the Canadian Shield. They fall into three well-defined groups, each separated from the next by a profound unconformity. The lowest forms a "basal complex" of gneisses and schists associated with much-altered sediments and lava flows. The second is similar in complexity but has a basal conglomerate with boulders of the older rocks, and is separated from the latter by a regional unconformity. The youngest group of the Pre-Cambrian rocks in Australia comprises a very thick conformable sequence of strata with interbedded tillite. It was separated from the older systems by a period of intensive orogeny and granitic intrusions on a vast scale. This igneous activity produced the phenomenal gold deposits of Kalgoorlie and the rich lead and silver ores of Broken Hill. In fact, it was the most important ore-forming epoch in all the history of Australia.

The Late Pre-Cambrian system is so much less deformed than the rocks below that it was long thought to be a part of the Cambrian. "It was perhaps the most extensive and, in some respects, is the most interesting sedimentary formation in the whole of Australia. It now covers an area of about 310,000 square miles, and the sea in which it was deposited formerly covered fully half the entire area of Australia."[11]

In New South Wales, where this system has a thickness of probably 13,000 feet, it includes at least three horizons of interbedded tillite, of which the greatest, the *Sturtian tillite,* is locally 600 feet thick.

Africa. A large part of the continent of Africa south of the Sahara is formed of Pre-Cambrian rocks (Fig. 50), and, although not fully studied, they evidently compare well in thickness and complexity with those of Australia and North America. Here, as elsewhere, the ancient complex includes thick systems of sedimentary rocks and

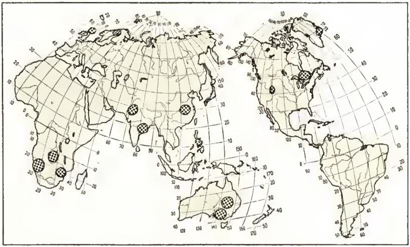

FIG. 69. Map showing the distribution of Pre-Cambrian glaciation (*coarsely stippled areas*). Base map by courtesy of the American Museum of Natural History.

volcanics which have been deformed and intruded by vast granitic batholiths. Here also rich deposits of precious metals were a by-product of the igneous activity. The most phenomenal of the African deposits are the gold-bearing conglomerates of the Witwatersrand in the Transvaal, which up to 1930 had yielded over $5,000,000,000 worth of the metal. Between 1940 and 1945, the Witwatersrand reached a peak production of more than 14 million ounces in a single year, valued at over $500,000,000. This is approximately half the world production.

CLIMATES

In rocks so old and so generally devoid of fossils there is little to indicate what the normal climates of the Pre-Cambrian actually were. The thick limestones were probably deposited in rather warm seas,

and the mud-cracked redbeds clearly imply marked seasonal rainfall. Most of the other formations, however, are equivocal in the light of our present understanding.

The most remarkable and direct evidence of Pre-Cambrian climate is the glacial deposits which occur in many parts of the world and represent at least two times of extensive continental glaciation, one in the middle Pre-Cambrian and the other near its close (Fig. 69).

Eliot Blackwelder.

Fig. 70. Late Pre-Cambrian tillite. South side of Little Mountain, west of Ogden, Utah. Note the large angular boulder in a fine-grained matrix. The compass above it has a diameter of 3 inches.

The Huronian (Gowganda) tillite has been mentioned. Its distribution over the southern part of the Canadian Shield shows that a continental ice sheet more than a thousand miles in diameter lay over central Canada for a time during the Huronian epoch.

Glacial deposits are widespread in northern Utah beneath the Cambrian formations, outcropping in the islands in Great Salt Lake and in the mountain ranges both east and southwest of the lake (Fig. 70). Tillite and glacio-fluvial deposits occur at different horizons in a series of sandy and shaly formations that exceed 12,000 feet in thickness and are supposedly of Pre-Cambrian age, possibly Beltian.

The tillite includes boulders of many kinds of rock, some of them as much as 10 feet in diameter, enclosed in a nonbedded, slaty matrix. Some of the boulders are faceted and striated. The tillite reaches the exceptional thickness of 700 feet at one locality and 1100 feet at another but is generally much thinner. Its age, unfortunately, is not definitely fixed. The series bearing the tillite rests upon a much older and intensely metamorphosed group of schists, and is overlain with local unconformity by beds high in the Lower Cambrian. The glaciation is believed to have occurred late in the Proterozoic era, but conceivably came early in the Cambrian.

Perhaps the greatest record of Pre-Cambrian glaciation exists in Australia, where ancient tillite is found at three horizons in a very thick series of late Pre-Cambrian formations. One of the finest displays of the glacial deposits is in the Flinders Range of south-central Australia, where the *Sturtian tillite,* exceeding 600 feet in thickness, forms the backbone of the range and is exposed in great cliffs. It consists of a nonbedded matrix of ancient "rock flour" and angular chips, in which boulders of many kinds of rock are embedded.[12] These boulders are in part rounded and in part angular, and some of them are faceted and striated. The underlying, well-bedded strata include scattered boulders of glacial origin that are believed to have been dropped from icebergs in a body of water in front of the ice sheet. The Sturtian tillite is about 1500 feet below the base of the Cambrian system in this section. The glacial deposits are known to extend for at least 300 miles from south to north.

In South Africa there are Pre-Cambrian glacial deposits of two widely separated ages,[13] the Numees tillite of Southwest Africa being apparently of late Proterozoic age, as are thick tillites in Katanga, west of Lake Tanganyika, whereas glacial deposits in Griqualand and the Transvaal, believed to be due to rafting by icebergs, appear to be of later Proterozoic time. The material of the glacial deposits in South Africa is thought to have come from farther north.

In the Yangtze Valley of China there are also extensive deposits of Pre-Cambrian glaciers. Scattered exposures of tillite indicate that glacier ice once spread over an area of at least 800 miles from east to west across central China during Pre-Cambrian time.

There are other tillites, less certainly dated but probably of late Proterozoic age, in Norway, East Greenland, India, and Australia. Certain of these underlie the Cambrian so closely that some geologists believe they belong in the Cambrian rather than the Pre-Cambrian.

Before the enormous length of the Pre-Cambrian was appreciated, the discovery of these evidences of early glaciation seemed a serious obstacle to the belief that the Earth was originally molten. To the older geologists, who conceived of the Earth in these early times as a hot planet clothed in dense vapors of a vast primal atmosphere, it was, indeed, a shocking discovery. In view of our present knowledge, however, the oldest of the known glacial times may have followed the first solidification of a crust by 500,000,000 years or more. Pre-Cambrian glaciation has, therefore, no greater bearing on the mode of origin of the Earth than later times of refrigeration. As we shall see, climatic changes on the Earth have been cyclic, with fluctuations between mildness and glaciation since early geologic time. The glacial times of the Pre-Cambrian were undoubtedly but relatively short episodes in the climatic fluctuations of those early ages. It must not be supposed that the world was generally cold for long times.

Evidences of Life before the Cambrian

For more than 50 years an eager search for fossils has gone on wherever Pre-Cambrian rocks have been studied—and the reward has been amazingly slight.

The most abundant fossils are the deposits of calcareous algæ, one of the most primitive tribes of microscopic plants that grow in moldlike colonies, precipitating calcium carbonate to build up globular or irregular structures with a fine concentric lamination (Figs. 71, 72, and 349). Such plants are common in the modern oceans and in lakes and streams. They have formed characteristic limy deposits of the same sort in all ages since early in the Pre-Cambrian. They are abundant in certain of the limestones and calcareous shales in the Beltian system in Montana (Fig. 71) and in limy zones in the Grand Canyon system. Similar structures occur in the iron-bearing rocks about Hudson Bay (Fig. 72) and in Michigan and Minnesota, some of them in the upper part of the Keewatin system in Minnesota. No higher types of plants are indicated in any part of the Pre-Cambrian record.

The best evidences of animal life are the trails and burrows of wormlike creatures in some of the Beltian rocks (Fig. 73). Sponge spicules were reported from the Grand Canyon beds, but they need verification. Recently the impression of a supposed jellyfish was reported from near the middle of the Grand Canyon system.

A number of other alleged fossils have been reported but are now suspected of being concretions or other inorganic structures. The first

of such objects to claim attention was named *Eozoön canadense* ("dawn animal of Canada"). These are hemispheric masses from a few inches to a few feet across, showing a crude concentric lamination of alternating layers of calcite and serpentine. The best and the original examples came from Côte St. Pierre about 35 miles east of Ottawa in a zone of intense contact metamorphism about 300 feet across,

C. L. and M. A. Fenton.

FIG. 71. A large colony of the calcareous algæ, *Collenia* sp., in the Siyeh formation of the Beltian system. Hole-in-the-Wall Cirque, Glacier National Park.

where the Grenville limestone is intruded by granite. In view of this occurrence, and of the fact that serpentine is a metamorphic mineral and is never found in undoubted fossils, *Eozoön* is now considered to be an inorganic structure. However, undoubtedly calcareous algæ similar to those of the Beltian occur also in the Grenville limestone.[7]

Another alleged fossil was found in the Early Pre-Cambrian (Seine River beds) at Steeprock Lake in Ontario. It takes the form of hemispherical or rounded masses showing a faint radial structure, but microsections prove that the material consists of fine quartz crystals. The structure can be so perfectly matched in near-Recent concretions that there is now no reason to believe these things to be organic deposits.

More remarkable is the oft-quoted report of Radiolaria in the Proterozoic schists of Brittany, from which forty-four species have been described and illustrated. But the amazing fact is that, although the rock is a quartz-schist and therefore much recrystallized and squeezed, all the published figures show whole uncrushed shells. Furthermore, all the "fossils" came from a single thin section and are far smaller than modern radiolarians. These objects are therefore suspected of recording a fertile imagination instead of a form of ancient life.

E. S. Moore.

FIG. 72. Weathered surface of a calcareous algal reef in the Upper Huronian series on Belcher Islands, Hudson Bay. The largest colony has a diameter of about 15 inches.

Two types of objects from Pre-Cambrian rocks have been described as arthropods. The first, found in the form of black carbonaceous patches on the bedding planes in some of the Grand Canyon shales, was named *Beltina danæ,* and was alleged to be similar to the eurypterids of the middle Paleozoic; but the present belief is that, at most, *Beltina* is no more than the film left by a bit of seaweed. The other supposed arthropod was described from the Pre-Cambrian of southern Australia and named *Protaledadia;* it is probably concretionary and inorganic—certainly there is nothing about it to justify the confident interpretation given by its discoverers.

Thus the record boils down to calcareous algæ and the trails and burrows of a few wormlike animals, possibly a few sponge spicules and doubtful protozoans—certainly not an impressive array to repre-

sent the life record of more than three-fourths of the history of the Earth!

On the other hand, a vast amount of carbon is disseminated in the Pre-Cambrian shales and schists. Later sedimentary deposits contain much carbon of organic origin which appears as coal, or as hydrocarbons, or as disseminated particles in dark shales. No other source is known for such disseminated carbon in sedimentary rocks, and the belief is therefore commonly held that the graphite and disseminated carbon in Pre-Cambrian rocks are also of organic source. Nevertheless, it appears probable that the hydrothermal reactions at the borders of large intrusive masses could break down atoms of $CaCO_3$ and free the carbon. The graphite in some Pre-Cambrian contact metamorphic deposits is believed therefore to be of such inorganic origin, and some students have argued that all the Pre-Cambrian graphite might be inorganic. Recently it has been found that the ratio of the isotopes of carbon, C^{12} and C^{13}, is higher in organically concentrated carbon than in that from inorganic sources, and the application of this criterion to various graphitic deposits in the Pre-Cambrian schists of Finland has given conclusive evidence that they are the residue of organic matter.[14]

C. L. and M. A. Fenton.

FIG. 73. Worm burrows (packed with sand) in the Siyeh formation of the Beltian system. Dawson Pass, Glacier National Park, Montana.

We may infer, therefore, that life probably was abundant in the seas of Pre-Cambrian time, especially during the Proterozoic, but was of a low order and doubtless small and soft-tissued, so that there was little chance for actual preservation as fossils.

Probably the greatest contrast between that primeval world and the world of today lies in the primitive character of both plant and animal life. No forests then mantled the mountain slopes, no prairies covered the plains, and no animals inhabited the desolate lands. Only in the sea was there a beginning of the organic host that in later times would possess the whole world.

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Collateral Reading

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A critical survey of the evidence.

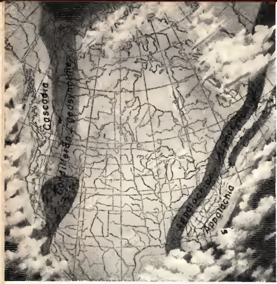


Fig. 74A (left). Early Cambrian paleogeography of North America. Land areas lightly shaded; shallow sea deeply shaded; deep sea horizontally lined. Present outcrops in solid black. Stumps of the late Pre-Cambrian ranges in the Canadian Shield are indicated.

Fig. 74B (right). Middle Cambrian paleogeography of North America. Symbols as above. Clouds in these and other maps have no climatic implications; they are used merely to hide areas of uncertainty.

Fig. 74C (left). Late Cambrian paleogeography of North America. Symbols as above. The Ouachita geosyncline appears in this epoch for the first time.

III. THE PALEOZOIC WORLD

CHAPTER 7

THE CAMBRIAN PERIOD

"The race of man shall perish, but the eyes
Of trilobites eternal be in stone,
And seem to stare about in mild surprise
At changes greater than they have yet known."

—T. A. CONRAD.

A Date of Reckoning. With the basal Cambrian rocks, fossils make their appearance in abundance, supplying at once a record of life and a certain means of correlating the physical record from place to place. Henceforth events in all parts of the world can be pieced together as parts of a continuous story, and it is possible to present the history of a whole continent, or of the whole world, in systematic fashion, period by period. Thus the beginning of the Cambrian is a date of reckoning in geologic history.

PALEOGEOGRAPHY AND PHYSICAL HISTORY OF NORTH AMERICA

The Cambrian Submergence. At the very outset of the Paleozoic era the Cambrian seas began to encroach upon the lowest lands, and before the close of the period covered more than 30 per cent of the present continent. When the older Cambrian rocks are plotted on a map, however, a striking relation is shown (Fig. 74*A*). They are not distributed over the present lowlands or along the margins of the continent, but are limited to two comparatively narrow belts well inland. In these places Cambrian formations attain a great thickness and abound in marine fossils, showing that seas were present here for a very long time. Since the sediments are of types that form in shallow water, it is clear that these places were vast troughs, subsiding slowly as they filled; that is, they were typical *geosynclines*. The eastern seaway followed the trend of the present Appalachian folds and is therefore known as the *Appalachian geosyncline;* the western,

centered in the Cordilleran region, is known as the *Cordilleran geosyncline.*

East of the Appalachian geosyncline lay *Appalachia,* a land mass of unknown eastward extent that was to form the Atlantic margin of the continent throughout the long Paleozoic era, rising at times to mountainous heights and supplying most of the sediment that filled the geosyncline. A similar marginal land, *Cascadia,* lay to the west of the Cordilleran geosyncline, while the vast interior of the continent was low plains. The mutual relations of these five major structural features of the North American continent are shown in Fig. 75.

Before the close of the Cambrian, another geosyncline, the *Ouachita trough,* took form across northern Mexico, Texas, and Oklahoma; and

Fig. 75. Profile across the North American continent in Cambrian time (*black*), to show the relations of the geosynclines and borderlands to the modern continent (*broken line*). The section runs through San Francisco and Washington, D. C. Vertical scale greatly exaggerated.

a corresponding borderland, *Llanoria,* stretched away to the south into the region that is now the Gulf of Mexico (Fig. 74*C*).

These seven elements persisted as the dominant features of the North American continent through all the changes of the Paleozoic era—three borderlands, three geosynclines, and a great stable interior. The borderlands were from time to time worn low, but were repeatedly uplifted; they were the mobile areas—the lands of Paleozoic mountains—while the interior of the continent remained relatively low and quiet until near the end of the era. The geosynclines trapped most of the debris eroded from the adjacent lands and would soon have been filled if they had not continued to sink. In them we find the most complete record of Paleozoic times in strata that reach an aggregate thickness of 30,000 to almost 50,000 feet along the axes of the troughs. During much of the era they were occupied by shallow seas, but at times they were drained by uplift or filled somewhat above sealevel with fluvial sediments.

Cambrian rocks are now exposed in only a small part of the area of these old geosynclines, because in many places they are buried by younger formations and in others they have been removed by post-Cambrian erosion. But wherever the rocks in two outcrops carry the

same marine fossils, it is clear that they were formed in a common seaway. Conversely, where the faunas in one area are conspicuously different from those in another, a barrier may be indicated. In the Lower Cambrian formations of the Cordilleran trough, for example, certain genera and species occur south of Idaho that are not found in Canada, and vice versa. The absence of Early Cambrian rocks in Idaho and western Montana would seem to confirm the implication that a land barrier had blocked the trough here. Detailed study of the lithology in adjacent outcrops adds to the evidence, for the formations become coarser and unfossiliferous as we approach Idaho from either north or south. It is inferred, therefore, that the Cambrian seas invaded the Cordilleran geosyncline in separate embayments that did not quite meet until near the close of Early Cambrian time. In the East, likewise, it is inferred that the *Acadian trough* (Fig. 74*B*) was separated from the Appalachian trough during most of Cambrian time because the faunas in the Acadian belt are so distinct from those farther northwest.

The Early Cambrian seas were restricted to the geosynclines and probably at no time covered more than 10 per cent of the continent (Fig. 74*A*). During the Middle Cambrian the area of submergence was even smaller in the East, where the marine waters were restricted to the middle and southern part of the Appalachian geosyncline and to the narrow Acadian trough. Meanwhile, however, the marginal highlands had been gradually reduced, and late in the epoch the western sea began an eastward expansion that developed rapidly, flooding the *Ouachita trough* (Fig. 74*C*) and spreading simultaneously across the northern states to the Great Lakes region, where it joined with the waters of the Appalachian geosyncline. When this flood was at its height, fully 30 per cent of the continent was submerged.

It must not be supposed that these Cambrian seas spread and receded with the violence of floods, for the time involved was more than 70,000,000 years, and the movements were probably like the broad crustal warping that has caused the drowned or the emergent condition of some of the modern coastlines. The northern part of the Baltic coast of Sweden, for example, is said to be rising now at the rate of 1 centimeter a year. In the course of a normal human lifetime this rise would amount to less than 3 feet, but in 10,000 years it would tilt all the water out of the Baltic Sea and turn it into dry land, or, if continued for a million years, would uplift the region as high as Mt. Everest, as noted by Shand.

Nor should we imagine that the Cambrian submergence was as simple as here sketched. Evidently the spread and final retreat of the Cambrian seas were largely the result of a world-wide rise and fall of sealevel, for contemporaneous changes were marked in other continents. The rise in sealevel may have been due in part to filling of the seas by sediments eroded from the lands, or to broad upwarping of parts of the ocean floor; and the retreat may have been caused by disturbances in other parts of the world, which deepened the ocean basins, thus drawing off the waters from the continents. Whatever the cause of this major cycle of submergence and emergence, minor oscillations were superposed upon it. Twice during the period the seas were greatly restricted if not entirely withdrawn from the continent, thus producing natural breaks in the record which make it convenient to separate the Cambrian *system* into three *series*, Lower, Middle, and Upper. Furthermore, while sealevel was rising and falling, the continent itself was slowly warping, even as it is today, and, accordingly, the outlines of the inland seas shifted widely during the period. The geosynclines, however, were the most continuously depressed areas and remained the most persistent seaways.

Reduction of Marginal Lands. Throughout this long period North America enjoyed a stability that contrasts strikingly with the mountain making of late Pre-Cambrian time. No evidence is known of any volcanic activity upon the continent, nor of any mountain making. During these millions of years of quiet and stability, the highlands inherited from the Proterozoic era were gradually reduced to monotonous flatness, and Late Cambrian America must have been largely devoid of scenic beauty.

Close of the Period. The Cambrian submergence was followed by a gentle lowering of sealevel that drained the inland seas and left the continent fully exposed but very low and flat. This emergence caused a break in the sedimentary record, separating the Cambrian from the Ordovician period. During the exposure, however, there was no marked uplift in North America; accordingly, the Cambrian formations suffered little erosion, and when renewed submergence brought the Ordovician seas again into the geosynclines, the new deposits were laid over the Cambrian with slight physical evidence of the break. In many places, therefore, the boundary between the Cambrian and the Ordovician is not well marked and is still the subject of controversy.

This stands in contrast with conditions in western Europe, notably Wales, where the Cambrian formations include much volcanic mate-

rial and are unconformably overlain by the Ordovician, indicating that uplift, disturbance, and considerable erosion occurred at the end of the Cambrian. This is the type region where the Cambrian and Ordovician systems were established.

Stratigraphy of the Cambrian Rocks [1]

Stratigraphy is the study of the stratified rocks, their nature, distribution, and interpretation. As noted in Chapter 1, the character of a sedimentary deposit indicates the conditions under which it was laid down, and at the same time reflects the character of the adjacent lands. The Cambrian strata are in this way the basis for the interpretations of the physical history sketched above.

Subdivisions of the Cambrian System. Although the Cambrian system of rocks was first studied and named in Wales (1835), a country which the Romans called Cambria, it is more grandly displayed in the mountains of western North America, where a vast thickness of evenly bedded strata is exposed like pages of a colossal manuscript preserving the history of Cambrian time. In different parts of this area the thick Cambrian section is divisible into numerous formations, some local and others recognizable over considerable distances. Throughout the whole Cordilleran geosyncline it is possible to group these formations, however, into three great *series* representing three distinct *epochs* of Cambrian time (Figs. 76 and 77).

In accordance with the custom of using geographic names for geologic units, the Lower Cambrian has been called the *Waucoban series,* for the very long section at Waucoba Springs, California; the Middle Cambrian, the *Albertan,* for the fine sections in the Canadian Rockies of Alberta; and the Upper Cambrian, the *Croixian* (pronounced *croy·an*), for the exposures about St. Croix Falls, Minnesota. The threefold division of the Cambrian is recognizable throughout the world, though local names are used in different countries.

The *Lower Cambrian* formations are characterized by faunas in which the spar-tailed trilobite *Olenellus* is conspicuous (Fig. 76, and Pl. 1, fig. 10). Since extensive experience has shown that no species of this genus occurs above the Lower Cambrian, *Olenellus* is accepted as a *guide fossil* or *index* to the Lower Cambrian series.

Above the zone of *Olenellus* come large-tailed trilobites of several genera, such as *Olenoides* and *Bathyuriscus* (Fig. 76; Pl. 1, fig. 3), which are equally distinctive of the *Middle Cambrian* formations. Finally, the *Upper Cambrian* faunas are characterized by the trilobite

Crepicephalus (Fig. 76, and Pl. 1, fig. 2) and by other genera which are confined exclusively to that epoch.

With *Olenellus* are associated many other types of trilobites, brachiopods, etc., that together represent the life of Early Cambrian time. The assemblage found with *Bathyuriscus* is largely different, for while many of the genera ranged from Early into Middle Cambrian time, the species are wholly distinct. Hence it is possible to distinguish

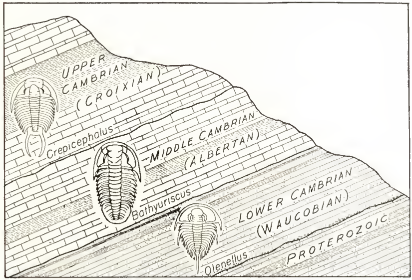


FIG. 76. Idealized section of Cambrian rocks to show the paleontologic basis for recognizing three series. The spelling Waucoban is now preferred to Waucobian.

the two series even where neither *Olenellus* nor *Bathyuriscus* occurs. Likewise, Middle and Upper Cambrian formations can be distinguished by the general composition of their faunas.

The cause of the abrupt change in the faunas between Early and Middle Cambrian time must be sought in a temporary withdrawal of the seas from the geosynclines, followed by an interval of nondeposition during which *Olenellus* died out and species of other genera evolved, so that the eventual return of marine waters into the geosyncline introduced a migrant Middle Cambrian fauna that had been developing in the marginal seas during the interval of nondeposition. Emergences of this sort, more or less complete, have caused the breaks between series, just as greater and more extensive emergences have separated the systems and divided off the periods of time. The Lower

Cambrian emergence is confirmed in most places by an abrupt change in the character of the sediments or by erosional unconformity or by basal conglomerates in the overlying series. The emergence was accompanied by no pronounced crustal disturbance, however; hence no angular discordance exists, and the Middle Cambrian seas returned to almost the same areas that had been flooded before. The emergence between the Middle and Late Cambrian epochs was apparently less extensive. The boundary between the Middle and Upper Cambrian series is therefore somewhat arbitrarily drawn at the first appearance of a new, immigrant fauna (the *Cedaria* fauna) that introduces stocks of trilobites which dominate in the Upper Cambrian formations.

Cambrian Rocks of the Cordilleran Trough. Along the axis of the Cordilleran geosyncline the Cambrian strata are several thousands of feet thick, and are now magnificently exposed as a result of uplift in the modern mountains. The Canadian Rockies of Alberta provide many exposures like those of Figs. 77 and 79, where the entire thickness of Cambrian rocks may be seen in a single view. Other fine sections are found in the Rockies of Mon-

CHARLES D. WALCOTT.

Fig. 77. South face of Mt. Bosworth, from Kicking Horse Pass, Alberta, showing in simple succession more than 12,000 feet of Cambrian strata.

tana and Wyoming and in the basin ranges of Utah and Nevada.

In general, throughout this region, the Lower Cambrian deposits consist chiefly of quartzite, and exceed half a mile in thickness. Some zones are shaly, and others, especially in the upper part, are calcareous, but the overwhelming predominance of sandy sediments is re-

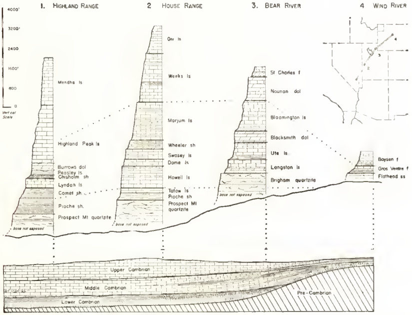


FIG. 78. Cambrian rocks of the Cordilleran trough. Above, four columnar sections whose positions are indicated on the inset map and whose vertical scale is shown at the left; below, a restored stratigraphic section, drawn on a vertical scale only about one-fourth as great as the corresponding columnar section. Data from Charles F. Deiss and from H. E. Wheeler.

markable. These sands were derived from the crystalline Pre-Cambrian rocks that had been weathering during the preceding interval. In some of the thickest sections, the basal part is unfossiliferous and probably was laid down in advance of the sea, but the presence of trilobites and other fossils indicates that most of the deposits are marine. The water must have been shallow, however, to permit the sand to be transported and spread evenly over the floor of the geosyncline.

The Middle Cambrian formations are predominantly limestones, all the way from Nevada to Alberta, indicating that by this time the bordering lands had been largely stripped of their sandy mantle or

were so low that little detrital sediment was being carried to the sea. These calcareous formations range from half a mile to a mile in thickness in the Canadian Rockies and in Utah and Nevada. During this epoch the geosyncline widened somewhat, and the sea tended to spread farther east than in Early Cambrian time; along this margin, where the Mid-Cambrian comes to rest directly on the Pre-Cambrian, it, too, is sandy like the Lower Cambrian (Fig. 78).

The Upper Cambrian series is largely dolomite and limestone throughout most of the Cordilleran trough, and is commonly 3000 to 4000 feet thick. Many of the towering white cliffs of the Canadian Rockies are made of these limestones (Fig. 79).

Cambrian Rocks of the Appalachian Trough. In the Appalachian trough the Lower Cambrian strata are predominantly detrital as they are in the West, whereas the Middle and Upper Cambrian consists largely of limestone and dolomite. This change in facies (lithologic expression) is due in part to the fact that Appalachia was undergoing rapid erosion during Early Cambrian time but was too low to supply much detrital sediment during the later epochs. Perhaps equally important was the fact that during the Early Cambrian the

NOTMAN.

Fig. 79. Mount Lefroy, in the Canadian Rockies northwest of Banff, Alberta. This peak, with an altitude of 11,660 feet, is made of Middle and Upper Cambrian limestones.

geosyncline was bordered on both east and west by a surface of Pre-Cambrian crystalline rocks, which had been weathering so long that an extensive sandy mantle was at hand to be swept into the newly formed geosyncline.

From Pennsylvania southward the detrital part of the Lower Cambrian series ranges from 3000 to 4000 feet in thickness, and its thick quartzites, being exceptionally resistant, are prominent ridge makers in the eastern part of the fold belt.

Carl O. Dunbar.

Fig. 80. Upper Cambrian (Potsdam) sandstone. Ausable Chasm, near Keeseville, New York.

The Middle and Upper Cambrian dolomites are sparingly fossiliferous and have been difficult to differentiate and to separate from the overlying Ordovician dolomites. They underlie a large part of the limestone valleys in the fold belt.

Cambrian formations are thick in the northern part of the Appalachian geosyncline, especially in eastern New York and the Champlain Valley of Vermont and in Newfoundland; but in the Champlain Valley they have been so badly deformed by later orogeny that the stratigraphy is still not well known.

Around the north and east flanks of the Adirondacks the Upper Cambrian overlaps onto the Pre-Cambrian granite and is largely detrital, consisting of the sand swept off the old Adirondack dome. Here it is known as the Potsdam sandstone (Fig. 80).

Cambrian Deposits of the Mississippi Basin. The Upper Cambrian seas gradually flooded across the low interior of the continent, lapping northward upon the ancient crystalline land of the Canadian Shield. Spreading thus across a region deeply covered by a residual mantle (much of which was wind-blown sand), they reworked this loose material into sandy and silty formations of vast areal extent but no great thickness. The exposures of these formations in the region of St. Croix Falls in Minnesota and Wisconsin are regarded as the type section of the Upper Cambrian and give us the name Croixian series. Here they attain a total thickness of scarcely 1000 feet.

Farther south, in the Ozark region of Missouri, the Upper Cambrian formations lap up onto the flanks of Pre-Cambrian hills which were

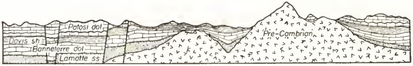


Fig. 81. Cambrian formations near the crest of the Ozark Dome. The unconformable overlap of successive formations on the Pre-Cambrian granite core shows that the dome was progressively submerged during Cambrian deposition. Length of section about 12 miles; vertical scale 5 times the horizontal. Normal faults at the left are of post-Cambrian date. After C. L. Dake, Missouri Bureau of Geology and Mines.

progressively submerged during late Cambrian time (Fig. 81). At the base of this section is 300 to 400 feet of sand like that of the upper Mississippi Valley, but the rest of the section is mostly dolomite, in part highly siliceous or cherty. This section represents the Ouachita trough and, in general, is similar to those exposed farther west in the Arbuckle Mountains of Oklahoma and the Llano uplift of central Texas. It is noteworthy that throughout this region the Upper Cambrian rests directly on Pre-Cambrian crystallines; clearly, the Ouachita geosyncline did not begin to form until after Middle Cambrian time.

Climate

There is no direct and certain evidence as to the climate of this remote period. The tillites which underlie the Cambrian in various parts of the world have been described in the discussion of the Proterozoic. Although some geologists regard them as basal Cambrian, we believe they belong with the underlying system. In any event, the extensive limy reefs of the pleosponges (Fig. 83) in the Lower Cam-

brian are believed to imply a mild climate, since physico-chemical conditions greatly favor the precipitation of limy deposits in *warm* waters. The wide distribution of many of the Cambrian species from low to high latitudes clearly suggests that climatic belts were less sharply defined than at present. The extensive deposition of pure limestones and dolomites during Late Cambrian times as far north as Quebec, Newfoundland, and northern Greenland likewise gives evidence of mild temperatures at these high latitudes.

Life of the Cambrian

The Curtain Rises. At the dawn of the Cambrian, life had already existed on the Earth for possibly a thousand million years. It is small wonder, therefore, that nearly all the great branches of the animal kingdom were represented, and that complex forms of arthropods, such as trilobites, held the center of the stage. Although exceedingly rare in the Pre-Cambrian rocks, fossils appear in abundance at the base of the Cambrian, revealing this highly varied life as though a curtain had suddenly lifted on a drama already in progress.

The lands must then have presented scenes of stark desolation, for Cambrian rocks bear no direct evidence of terrestrial life of any sort. Primitive soft-tissued plants, such as lichens, probably clothed the moist lowlands, but, lacking roots and vascular tissue by which to draw moisture from the ground, these lowly plants could not thrive in the dry regions. Animals had not yet learned to breathe air and did not appear on the land until nearly the whole of three more geologic periods had passed.

The seas, however, teemed with invertebrate animals of many kinds, finding both food and shelter among the varied and abundant seaweeds. On the whole, it was a strange and unfamiliar assemblage of animals, primitive in many respects and all of comparatively small size.

Stars of the Cast. The dominant creatures of the Cambrian seas were the *trilobites* (Fig. 82), swimming and groveling arthropods which became so numerous and varied as to make up fully 60 per cent of the known fauna (see Pl. 1). They are by far the most important fossils in the Cambrian rocks. In their day they boasted the greatest size if not the highest intelligence of any animals upon the Earth. Even so, they were small, generally ranging between 1 and 4 inches in length. The giant of Cambrian forms was *Paradoxides harlani* (Fig. 82; Pl. 1, fig. 6), whose abundant remains in Middle Cambrian slates

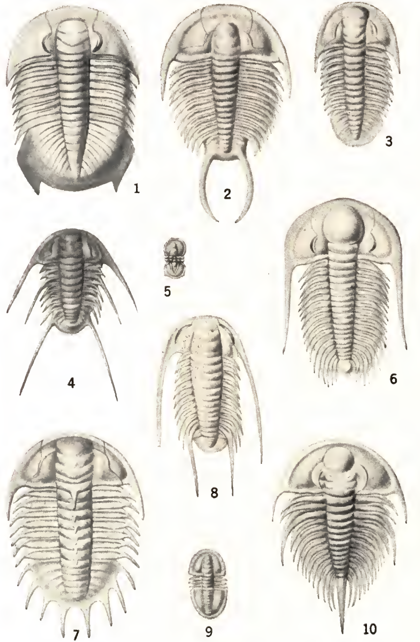


Plate 1. Cambrian Trilobites.

Upper Cambrian: Fig. 1, *Dikelocephalus minnesotensis;* 2, *Tricrepicephalus texanus.* Middle Cambrian: Fig. 3, *Bathyuriscus rotundatus;* 4, *Albertella helena;* 5, *Agnostus interstrictus;* 6, *Paradoxides harlani;* 7, *Olenoides curticei.* Lower Cambrian: Fig. 8, *Bathynotus holopyga;* 9, *Eodiscus speciosus;* 10, *Olenellus thompsoni.* All natural size except 6, which is about $\frac{1}{6}$ natural size. Drawn by L. S. Douglass.

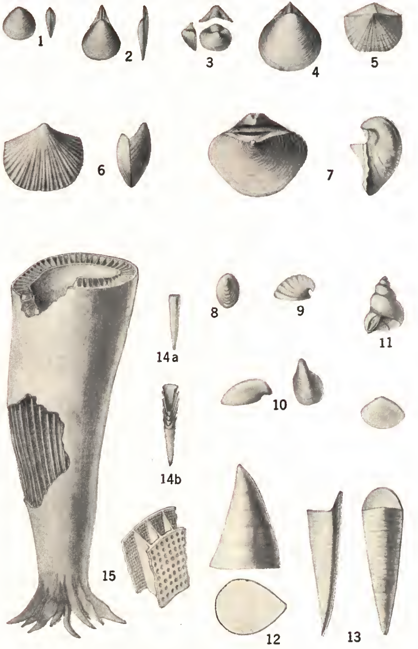


Plate 2. Cambrian Brachiopods (1–7); Molluscs (8–12), etc.

FIG. 1, *Dicellomus politus* (ventral and lateral views); 2, *Lingulepis pinnaformis;* 3, *Paterina bella;* 4, *Obolus aurora;* 5, *Billingsella coloradoensis;* 6, *Eoorthis texana* (ventral and lateral views); 7, *Kutorgina cingulata* (dorsal and lateral views); 8, 9, *Helcionella rugosa* and var. *paupera;* 10, *Helcionella* sp. (2 views); 11, *Matherella saratogensis;* 12, *Hypseloconus elongatus* (side view and outline); 13, *Hyolithes princeps* (lateral and dorsal views and operculum); 14, *Salterella rugosa* (entire and weathered shells); 15, *Cambrocyathus profundus* (lateral view and enlarged detail). All natural size, except Fig. 15 in part.

near Boston indicate a creature about 18 inches long and probably not over 10 pounds in weight. It is a striking commentary on the history of life that such feeble folk held undisputed sway over the Earth throughout Cambrian time—a span exceeding that of human existence by perhaps a hundredfold.

Next to the trilobites in importance came a horde of *brachiopods,* which constituted another 30 per cent of the Cambrian faunas (Pl. 2, figs. 1–7). During the early and middle epochs of the period these were mostly very small, primitive types (Atremata) with phosphatic shells. They must have been exceedingly numerous locally, for in places their shells now cover the bedding planes of the Cambrian rocks. In the Late Cambrian, more progressive types with calcareous shells began to rise into prominence, foreshadowing their dominance in the Ordovician period following.

The *Pleospongia* (also known as *Archeocyathinæ*) played the role of reef-builders in the Early Cambrian seas (Fig. 83; Pl. 2, fig. 15). They formed vase-shaped to cylindrical skeletons of calcite, characterized by having two walls, one inside the other, separated by limy plates or bars. Both walls were sievelike. Their biologic relations are still uncertain, but they are now believed to be an aberrant group of calcareous sponges. They generally grew over one another in

Fig. 82. Restoration of the Cambrian trilobite, Paradoxides harlani. About 1/4 natural size.

tangled profusion as sponges do, and they left an imposing record in the Lower Cambrian rocks in the form of reefs which are found in many parts of the world (California, New York, Quebec, Labrador, Newfoundland, New Siberia, Sardinia, Spain, Australia, and Antarctica). In Australia they range through fully 200 feet of limestones and extend for more than 400 miles; it is a strange coincidence that

T. G. Taylor.

FIG. 83. Weathered pieces of Lower Cambrian limestone showing natural sections of Pleospongia. Note millimeter scale at left.

this greatest of all Paleozoic reefs should occupy a region closely paralleling the Great Barrier Reef of the east coast of Australia, the largest of all modern coral reefs.

Mention must also be made of the calcareous alga, *Cryptozoön*, that formed smaller but widely distributed reefs throughout Cambrian time (Figs. 84 and 85). These deposits are hemispherical, irregular, or spreading masses of finely laminated calcite precipitated layer upon layer by moldlike colonies of microscopic blue-green algæ. The limy precipitate preserves only the gross form of the colony, not that of the individual plants.

Worms in considerable variety must have been present, and some of the sand flats apparently were full of them, since the sandstones

are in places replete with their burrows, making the so-called pipe-rocks (*Scolithus*, etc.). These are especially common in the Upper Cambrian sandstones of New York and Wisconsin and in the Lower Cambrian of Tennessee, Virginia, and Sweden.

Minor Characters. The remaining phyla play a very minor part in the fossil record of the Cambrian, partly because many of the modern classes had not yet evolved, but probably in greater degree be-

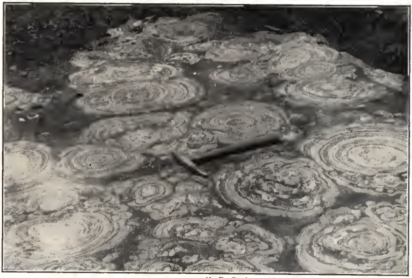
Eliot Blackwelder.

FIG. 84. Colonies of calcareous algæ weathering out of the Upper Cambrian Gros Ventre formation in Grand Teton quadrangle, Wyoming.

cause they had not developed shells capable of fossilization. *Protozoa* are not certainly known; simple "glass sponges" with siliceous spicules are locally abundant; and *cœlenterates* are of no importance, though doubtful impressions of jellyfish have been found locally in the Lower Cambrian of New York, Vermont, and the Baltic countries, and a supposed sea anemone has been found in the Middle Cambrian Burgess shale. The ancestors of the true corals had not yet learned to secrete lime. *Echinoderms* are represented by small, primitive *cystoids*, but no starfish, sea-urchins, or crinoids are known; nor were there any bryozoans.

Although the *molluscs* constitute the bulk of the shell-bearing animals of modern seas they were relatively few in Cambrian time. The *gastropods* were first to appear, and are represented by two distinct tribes in the Lower Cambrian rocks. The first group includes very

small and primitive *snail* shells scarcely attaining a breadth of half an inch and having the form of a low cone or of a spiral less than one-quarter of an inch across with only two or three volutions. The snails remained inconspicuous until near the close of the Cambrian, when a rapid evolution set in that foreshadowed the prominence they were to assume in the next period. Much more common than snails were the *hyolithids* (Pl. 2, fig. 13), doubtfully allied to the modern ptero-



H. P. Cushing, New York State Geological Survey.

FIG. 85. Natural exposure of part of a reef of the calcareous alga, *Cryptozoön proliferum.* Glacial scour during the Pleistocene epoch has removed the summits of these hemispheric colonies, exposing transverse sections. Saratoga, New York.

pods or sea butterflies, which are gastropods peculiarly modified for a swimming habit. The small scabbard-shaped shells of *Hyolithes* occur locally in such abundance as to form thin layers of limestones.

Pelecypods appear to have been absent throughout the Cambrian, and *cephalopods* appeared only near the close of the period and are among the rarest of Cambrian fossils. Two genera of minute conical shells from the Lower Cambrian rocks have been considered to be cephalopods, but this now seems highly doubtful. These are *Salterella* (Pl. 2, fig. 14) and *Volborthella,* both of which are confined to the Lower Cambrian.

The Burgess Shale Fauna. Probably the most significant fossil locality yet known was discovered by C. D. Walcott (Fig. 86) in 1910.

It is a bed of slaty black shale of Middle Cambrian date high up on the slope of Mt. Wapta above the town of Field, British Columbia. The fossils are preserved as delicate carbon films on the bedding planes where bedding and cleavage coincide. Each is a mere lustrous film, the residue of a soft body pressed as flat as the ink on this page, but it preserves with amazing detail the form of delicate external appendages and, in many instances, shows the presence of viscera. From this single bed, only a few feet thick, Walcott described 70 genera and 130 species, almost all of which were delicate soft-bodied animals of types elsewhere completely unknown. Among these are sponges, jellyfish, and a remarkable array of annelid worms in which not only the body form but also bristles, scales, and even intestinal tract are preserved. The most interesting, however, are the highly varied primitive arthropods, which include, besides trilobites with limbs and antennæ, delicate forms like the modern brine-shrimp. Of particular interest is a fossil onychophoran [3] (*Aysheaia*, Pl. 3, fig. 4; and Fig. 87). A single genus of this strangely isolated stock still survives and has long been recognized by zoologists as a persistently primitive type, structurally like the expected common ancestor of annelid worms and arthropods. It was confidently believed by comparative anatomists to be a relic of a very ancient stock, but, since it is as soft-bodied as a caterpillar, there seemed no hope of a fossil record until the Burgess shale was discovered.

Fig. 86. Charles D. Walcott (1850–1927), leading student of Cambrian faunas.

Fig. 87. Restoration of a Middle Cambrian onychophoroid, *Aysheaia pedunculata*. Natural size. After G. E. Hutchinson.

The Burgess shale fauna is important chiefly because of the perspective it gives. Here we get one clear view of the world of soft-bodied creatures that inhabited the early Paleozoic seas. Without these fossils we could only infer that life was abundant, and guess what it was like; and we might have believed that trilobites were more abundant than other animals

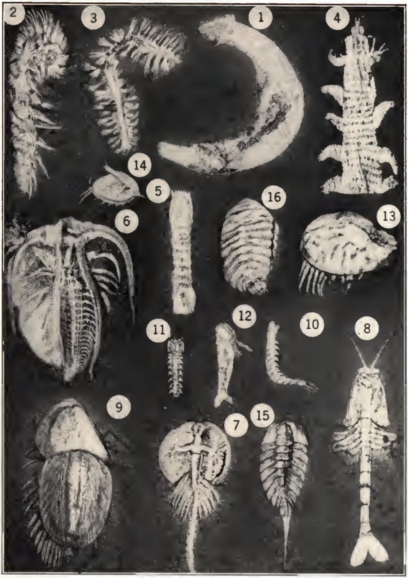


Plate 3. Middle Cambrian Fossils from the Burgess Shale, near Field, British Columbia.

Figs. 1–3, annelids (Chætopoda); 4, Onychophora (see Fig. 87); 5, 6, 9, Trilobita; 7–8, 10–12, Branchiopoda; 13–14, Phyllocarida; 15, 16, Merostomata.

Fig. 1, *Ottoia prolifica;* 2, *Canadia spinosa;* 3, *C. setigera;* 4, *Aysheaia pedunculata;* 5, *Mollisonia gracilis;* 6, *Marrella splendens;* 7, *Burgessia bella;* 8, *Waptia fieldensis;* 9, *Naraoia compacta;* 10, 11, *Yohoia tenuis;* 12, *Y. plena;* 13, *Hymenocaris ? circularis;* 14, *H. ? parva;* 15, *Molaria spinifera.* All after Walcott (1911–1912). Figures enlarged $\times 1\frac{1}{2}$ or $\times 2$.

just because they are the common fossils. This glimpse of the primitive soft-bodied creatures of the Cambrian sea proves the incompleteness of the fossil record; it also presents an exciting challenge. The wonderful discovery came by accident as a pack horse, high up on a mountain trail, turned over a slab of slate that caught the eye of a trained paleontologist. It was a spot where the forces of nature had conspired to preserve an almost incredible record from the past; there must be many others yet undiscovered—perhaps some in the Pre-Cambrian slates!

One may infer the circumstances under which this unusual deposit formed. Muds so fine of grain and so rich in decaying organic matter must have formed a soft, oozy sea floor, deficient in oxygen and reeking in hydrogen sulphide. Occasional storm waves stirring the bottom muds liberated the H_2S and allowed it to rise toward the surface, poisoning such swimming or floating organisms as were present. The locality of Mt. Wapta was probably a depression somewhat deeper than the surrounding sea floor, and when the dying organisms drifted into it they settled below wave base and were never again disturbed. Because of the poisoned water, no scavengers were present to devour them and so they remained whole, with limbs and other delicate appendages intact. Comparable mass destruction of organisms by H_2S gas rising from mud bottoms has been observed in modern seas.

Stage of Evolution Represented. Although the vast length of Pre-Cambrian time was not suspected when Walcott, in 1890, first brought out the richness and variety of Early Cambrian life, the zoölogist Brooks exclaimed that these forms, instead of being "the simple, unspecialized ancestors of modern animals, are most intensely modern themselves in the zoological sense and . . . belong to the same order of nature as that which prevails at the present day." Obviously the evidences of the truly primitive stages of life and of their differentiation into the great phyla must be sought far earlier than the Cambrian. It is a tantalizing thought that probably far more than half the drama of evolution had been enacted before the rising curtain gives us a clear glimpse into the Cambrian scene.

Even though it is now established that a great variety of animals must have existed in the Proterozoic era, the sudden appearance of abundant fossils in the Cambrian is remarkable. Proterozoic fossils are chiefly those of lowly, lime-secreting algæ, with possible representatives of three animal phyla, the protozoa, sponges, and worms; but the Cambrian strata of North America alone have yielded at least 1200 different kinds of animals, including sponges, cœlenterates,

worms, brachiopods, gastropods, echinoderms, and arthropods. The difference implies that some great change took place in the organization of animals during the interval between the Proterozoic and the Cambrian. This undoubtedly involved the use of external armor in the form of shells of chitin (a nitrogenous substance similar to our finger nails) or of calcium carbonate. Proterozoic animals were probably unarmored and, therefore, like the soft-tissued creatures of the Cambrian, were scarcely capable of preservation except under extraordinary conditions. The great variety of such forms in the Middle Cambrian Burgess shale, most of which are recorded nowhere else, shows clearly how abundant and how varied soft-bodied animals may have been in Pre-Cambrian time. The suddenness of the appearance of armor in several phyla at the beginning of the Cambrian may be more apparent than real, for the interval preceding the Cambrian is one of the greatest breaks in the geologic record and probably represents many tens of millions of years during which the evolution of shells was taking place.

The cause of the development of shells in many stocks of animal life in the time between the Proterozoic and the Cambrian has been a subject of much speculation. Brooks has suggested [4] that before this time marine animals were chiefly small free-floating or swimming creatures like the larvæ of existing types, and that near the close of the Proterozoic they began to inhabit suitable parts of the shallow sea floor, then rapidly increased in size, experienced for the first time the effects of crowding and keen competition, and hence required protective armor. It has also been postulated that the Pre-Cambrian oceans may have been so deficient in dissolved carbonates that limy shells could not be formed, that the lime brought to the sea by rivers may have been chemically precipitated as fast as it was supplied because of the decaying organic matter on the sea floor before scavenging types of life had developed.[5] This hypothesis does not really solve our problem, however, because even in the absence of lime, animals could still make their shells of chitin, as, in fact, most of the Lower Cambrian types did. Moreover, the abundance of deposits of calcareous algæ in Proterozoic formations rather strongly controverts the suggestion of a deficiency of lime in the oceans.

The development of actively predacious habits may have been the first great stimulus to the development of protective armor. It is not improbable that all Pre-Cambrian animals were herbivorous or scavenging, and that the development of the active carnivorous habit co-

incided with the great change that marks the lost interval before the Cambrian.

Faunal Realms. The modern shells along the New England coast are entirely different from those to be found on the coast of California, because the Atlantic and Pacific oceans have been effectively separated by land barriers while the modern species were evolving. Thus each ocean has become a great faunal realm so far as the marine invertebrates are concerned. How great the faunal differences are is strikingly shown at Panama, where Dall has listed 517 species of shell-bearing invertebrates from the Atlantic side and 805 from the Pacific, yet finds but 24 common to both oceans, though the barrier is less than 50 miles across! Obviously, marine animals could migrate more easily from our Atlantic coast to that of Europe than by way of the Arctic or Antarctic into the Pacific. Accordingly, there is much closer resemblance between the modern marine faunas of western Europe and eastern United States than between those of the east and west coasts of North America. It is therefore clear that, during a submergence of the continent, a sea which entered the interior from the Atlantic realm would bring animals quite distinct from those of a western seaway. Some of the Cambrian faunas show this distinction quite as definitely as the modern ones.

The Early Cambrian oceans seem to have been somewhat openly connected, so that intermigration was easy and the leading types of life are much alike in various parts of the world. The faunas of this epoch are therefore said to be *cosmopolitan.* On the contrary, the Middle Cambrian faunas of the Pacific and Atlantic realms are largely different. The former is characterized by the large-tailed trilobites of the tribe of *Bathyuriscus,* none of which is present in the Atlantic realm. In the latter, various species of the trilobite *Paradoxides* are common, though none has ever been found in the Pacific realm. Thus it is known that the Acadian trough in Middle Cambrian time was flooded from the Atlantic, bringing *Paradoxides* into this seaway across Newfoundland, Nova Scotia, and eastern New England at least as far as Boston (and by way of a special trough into northern Vermont), with species closely allied to those of Europe. The southern part of the Appalachian trough at the same time contained no *Paradoxides,* but was inhabited by genera that occur in the Cordilleran trough and the Pacific realm.

The distinction between realms is equally clear and more striking when we come to the Late Cambrian and find the *Dikelocephalus*

fauna spreading from the southwestern margin of the United States across Nevada, Texas, and Oklahoma, northward into Minnesota, and eastward into the Appalachian trough, while in Europe the contemporaneous seas swarmed with the tribe of *Olenus*, another large-tailed form.

Within each great realm there are provinces less sharply isolated by differences in temperature, depth, facies, or salinity. Thus the modern fauna of the Florida coast is unlike that of New England or Labrador, and even the two sides of Florida have somewhat different assemblages. A very slight change in salinity makes a great difference in the richness of the faunas of Long Island Sound and the New Jersey coast. Likewise, changes in temperature, due to Cape Cod's deflection of the cold Labrador current from the coast, are responsible for a marked difference in the faunas of the eastern and southern coasts of New England. In the same way, an embayment from Hudson Bay would bring into the continent a very different life assemblage from that of a Gulf embayment, though both would have the general impress of the Atlantic realm.

During the early stages of any general submergence, we should, therefore, expect localized faunas in distinct embayments. Should two or more such embayments eventually unite, the faunas would mingle, a keen struggle between competing types would ensue, many species would become extinct, and the resultant fauna would take on a more cosmopolitan aspect. This was the case in Early and in Late Cambrian times. Many of the apparently sudden changes in the faunas of the geologic past probably mean not so much a break in time as a downbreaking of barriers and an ingress of migrants.

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[2] *Cambrian Geography and Sedimentation in the Central Cordilleran Region;* by Charles Deiss. Bulletin of the Geological Society of America, Vol. 52, 1941, pp. 1086–1114.

[3] *Restudy of some Burgess Shale Fossils;* by G. E. Hutchinson. U. S. National Museum, Proceedings, Vol. 78, 1930, Art. 11.

[4] *The Origin of the Oldest Fossils and the Discovery of the Bottom of the Ocean;* by W. K. Brooks. Journal of Geology, Vol. 2, 1894, pp. 455–479.

[5] *The Limeless Ocean of Pre-Cambrian Time;* by R. A. Daly. American Journal of Science, 4th series, Vol. 23, 1907, pp. 93–115.

Collateral Reading

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Fig. 88A (left). Early Ordovician (Mid-Canadian) paleogeography. Land areas lightly shaded; shallow seas deeply shaded; deep sea horizontally lined. Present outcrops are in solid black.

Fig. 88B (right). Middle Ordovician (Black River-Trentonian) paleogeography of North America. Symbols as above. Clouds are used to hide areas of uncertainty and have no climatic implications.

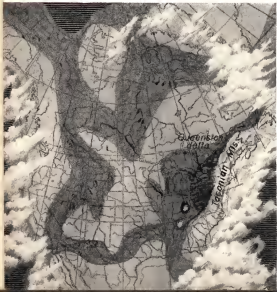

Fig. 88C (left). Late Ordovician (Richmondian) paleogeography of North America. Symbols as above. The largely nonmarine part of the Queenston delta is distinctly shaded.

CHAPTER 8

THE ORDOVICIAN PERIOD

"Yes, small in size were most created things
And shells and corallines the chief of these."
—T. A. CONRAD.

PHYSICAL HISTORY OF NORTH AMERICA

Greatest of All Submergences. The post-Cambrian emergence was only temporary. The continent still lay but little above sealevel, and the Ordovician submergence brought marine waters creeping in over the lowlands from east, west, north, and south in shallow epeiric seas that first flooded the geosynclines and eventually spread over much of the interior, covering at the maximum fully half of the present continent and reducing it to a group of great islands almost awash with the sea (Fig. 88*C*). No other submergence has been quite so extensive in North America.

Because of the flatness of the continent, slight local warping greatly altered the outlines of the shallow epeiric seas, a few feet of depression producing embayments of considerable extent, and slight uplift transforming great areas of the shallow sea floor into land. As a result, the shorelines shifted back and forth over the interior of the continent, and the paleogeography is very complicated in its details. Many maps would be required to present truthfully the slow ebb and flow of these marine floods. The three maps here presented (Fig. 88) indicate but three temporary stages in an ever-changing scene. Each shows a time of main submergence in a distinct epoch.

The early Ordovician seas entered the geosynclines first and there left an imposing record of thick limestones and dolomites, but the marine waters also spilled over and at times spread widely across the central and eastern part of the United States.

The greatest submergence came during the latter part of the Late Ordovician, when a vast sea spread southward from the Arctic across central Canada to join the southern embayments that occupied much of the United States. During this time Appalachia was steadily rising

into mountains, and at the end of the period the northern part, at least, was strongly thrust westward as the *Taconian disturbance* reached its culmination. As a result of this uplift and the consequent rapid erosion, the Appalachian geosyncline was filled with sands, muds, and gravel, and in the vicinity of New York and Pennsylvania a vast delta (*Queenston delta*) grew westward until it crowded back the shoreline to a point west of modern Niagara Falls (Figs. 88*C*, 99).

Four Stable "Domes." In the midst of these extensive seaways four relatively small areas stood out as persistent lands. These were: (1) the *Ozark dome* of southeastern Missouri, (2) the *Highlands of*

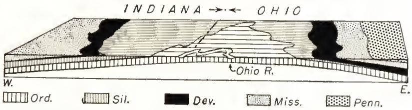

Fig. 89. Block diagram showing in its front face a west-east section across the Cincinnati arch near Cincinnati, Ohio. Length of section about 215 miles; vertical scale about 8 times the horizontal. Adapted from a section by G. D. Hubbard.

Wisconsin, (3) the *Adirondack dome* of northeastern New York, and (4) the *Cincinnati arch,* with its southern extremity sometimes distinguished as the *Nashville dome.* From the viewpoint of isostasy, each was a positive area tending to rise slightly as the surrounding regions subsided. Although none reached mountainous heights, all persisted as landmarks throughout most of Paleozoic time, flanked about by successive epeiric seas. They are now areas of relatively ancient rocks encircled by younger strata that dip gently away from the central area, and for this reason they are spoken of as *domes* or *arches* (Figs. 89, 81).

The most significant of the four was the *Cincinnati arch,* which ran northward from the vicinity of Nashville, Tennessee, through Cincinnati and western Lake Erie into Ontario, thus paralleling the western side of the Appalachian geosyncline. At many times during the Paleozoic era it served as a barrier separating the Appalachian seaways from those farther west. Even when partly submerged, it formed a threshold to limit the westward spread of detrital sediments derived from Appalachia.

The Cincinnati arch was never mountainous, or even a highland (Fig. 89), and it seems remarkable that a structure so broad and low

should have been so persistent. It began to form during the Middle Ordovician, was definitely outlined in the Silurian, and was further elevated at different times during the remainder of the Paleozoic era.

Temporary Emergences and the Subdivisions of the Period. Twice during the period there was gentle but apparently complete emergence of the continent. During these intervals the freshly formed sediments were exposed to erosion and locally more or less widely removed, though no folding or pronounced uplift distorted the exposed beds. At the same time there was crowding of the marine invertebrates upon the shallow continental shelves and more or less rapid evolution as diverse emigrants from the epeiric seas were driven into competition. As a result, the following submergence in each instance brought into the new seaways immigrant faunas in which the species and many of the genera were unlike those of the previous invasion. Thus, as in the Cambrian, the Ordovician system of formations is divisible into three series, each separated from the next by a widespread (though not prolonged) stratigraphic break, and each marked by distinctive faunas.

The Early Ordovician has been named the *Canadian epoch* for exposures in extreme southeastern Canada; the Middle Ordovician is known as the *Champlainian epoch* for its striking development along the Champlain Valley; and the Late Ordovician has been called the *Cincinnatian epoch* for exposures about Cincinnati, Ohio.

The system is exceptionally well displayed in New York State, where it was first comprehensively studied and classified. The succession of formations there exposed is therefore regarded as the *type* or *standard section,* with which others in America are compared. From this region also many of the Ordovician names are derived.

Taconian Disturbance and the Close of the Period. During the Ordovician period Appalachia was rising again, at first slowly and then with acceleration. This, the *Taconian disturbance,* culminated at the close of the period in a chain of fold mountains that extended from Newfoundland through the Maritime Provinces of Canada and New England and reached at least as far south as New Jersey. It resulted in close folding and westward overthrusting of the older rocks that now occupy a disturbed belt along the south side of the St. Lawrence and the east side of the Hudson Valley (Fig. 90). Remnants of such overthrusts may still be seen in the Taconic Range of eastern New York and in the shale belt of eastern Pennsylvania to the northeast of Harrisburg.[1] Sir William Logan long ago recognized that a great thrust fault follows the St. Lawrence Valley, separating

the intensely deformed rocks of its south shore from the relatively undisturbed ones on the north side. This dislocation has since become known as *Logan's line.* It was the locus of late Ordovician overthrusting (Fig. 90).

The disturbance began early in the period with local warping in northern Vermont and spread northeastward into Quebec and New-

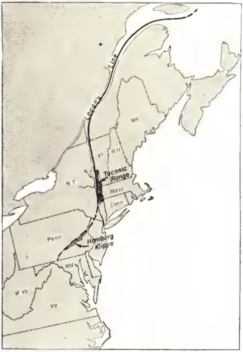

FIG. 90. Logan's Line, to the east of which the Ordovician and older strata are intensely deformed. The modern Taconic Range is a remnant of a late Ordovician thrust sheet, and the Hamburg Klippe is believed to be a southern remnant of similar origin. Data from E. B. Knopf and from George W. Stose.

foundland, where submarine thrust faulting gave rise to talus and landslide deposits on the sea floor; these deposits are now preserved as limestone breccias, locally of great thickness and of remarkable coarseness, embedded in dark shales (Fig. 91). The regional uplift in northern Appalachia stimulated erosion and resulted in an enormous volume of detrital sediment being carried into the geosyncline. During the Early Ordovician, these sediments were mostly fine dark muds, but as uplift continued, they included more and more sand and

CARL O. DUNBAR.

Fig. 91. Cow Head breccia, a talus deposit resulting from submarine thrust faulting during Ordovician time. Cow Head Island, western Newfoundland. Hammer above center gives the scale.

gravel and finally culminated in thick sandstones and conglomerates of Late Ordovician age that spread widely over areas where limestone had previously been forming.

This *first generation* of Appalachians no longer exists as mountains. The highest peaks disappeared through erosion before half a geologic period had passed, and the late Silurian sea advanced over the peneplaned folds; but a record was left in (1) the unconformity between Ordovician and younger rocks in the disturbed area and (2) the coarse detrital sediments deposited in the geosyncline.

Most of New England and Maritime Canada suffered two later disturbances, one in the Devonian and another in the Permian, and these largely mask the results of the Taconian disturbance; but in several places along the western margin of the disturbed belt, Ordovician formations can still be seen in folds truncated by erosion and overlain with striking unconformity by Silurian or younger beds. Fine examples may be observed along the Hudson Valley from Kingston to Catskill (Figs. 92 and 93). In eastern Quebec (Gaspé), also, the Ordovician formations are much more metamorphosed and deformed than the Silurian and commonly are overlain by the latter with angular discordance. These relations are well shown in the Matapedia Valley and farther east along the Bay of Chaleur.

Volcanic Activity. The Taconian disturbance was accompanied by volcanic activity, the first recorded in this region since before the Cambrian. Local volcanoes were in eruption in early Middle Ordovician time, spreading ash falls over the Appalachian geosyncline from Alabama to New York, and even as far west as Wisconsin, Minnesota, and Iowa. In central Pennsylvania, ten such ash beds have been recognized, intercalated in Middle Ordovician marine limestones (four in the Black River group and six in the Trenton group),[2] and in Alabama two are recognized. The ash beds vary in thickness up to more than 7 feet but commonly are only a few inches thick. A basic lava flow is associated with one of the ash beds near Jonestown, Pennsylvania,[3] and pillow lava occurs in Middle Ordovician shales at Stark's Knob in eastern New York; the greatest display of volcanic activity, however, is found farther to the northeast, in Quebec and Newfoundland. In the Bay of Chaleur region of eastern Quebec, the *Mictaw group* is made up of shales and volcanic tuff of great but undeter-

C. R. LONGWELL.

Fig. 92. Unconformable contact of Upper Silurian (Manlius) limestone on Middle Ordovician (Hudson River) shale at the Alsen quarry, south of Catskill, New York. The Silurian beds strike N 35° E and dip 20° NW, whereas the Ordovician beds strike N 5° E and dip 55° E.

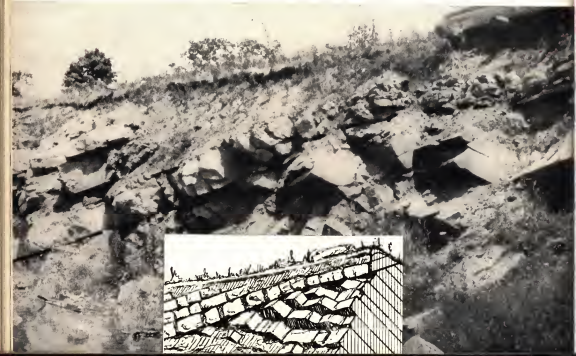

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Fig. 93. Unconformable contact of Upper Silurian (Manlius) limestone on closely folded Middle Ordovician (Hudson River) shale at Becraft Mountain near Hudson, New York. White dots follow the contact. Dip and strike symbols in white show structure at two places where the shale is crumpled and closely folded.

mined thickness. Eastern Newfoundland has tuff and pillow lavas interbedded with graptolite shales and fossiliferous limestones of Middle Ordovician age, and such volcanic rocks spread widely across the center of the island. Pillow lavas and agglomerate of great thickness are associated with the Ordovician sediments from Bay of Islands south to Port au Port Bay on the west coast of Newfoundland (Fig. 94).

Climate

Few species of animals or plants now range from southern United States into Canada, and probably none save man and his dog range from the subtropics into arctic latitudes. Alligators and palms do not live in Greenland, nor musk-ox and walrus in Florida, for each is imprisoned by the limits of a definite climatic belt. Ordovician

faunas, however, show little regard for latitude, many of the same species occurring in Kentucky, southern Ontario, the Mackenzie Valley, and northern Greenland. In the Upper Ordovician limestones there are small coral reefs widely distributed throughout arctic Canada, from Manitoba to Alaska and northern Greenland, all made of a few common species some of which occur also in Wyoming and New Mexico. We can not escape the conclusion, therefore, that climatic zones were less marked then than now, and that arctic America was not ice-bound at that time. The wide distribution of vast limestones and dolomites bears the same implication, for if parts of the oceans had been much warmer than others, they would have been the chief places of limestone deposition.

Tillites in the Varangerfjord region of northern Norway, long thought to be probably of Ordovician age, are now known to be probably Pre-Cambrian.[4]

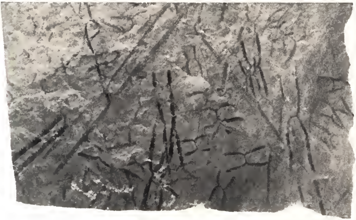
CARL O. DUNBAR.

Fig. 94. Pillow lavas interbedded with Middle Ordovician strata near the mouth of Fox Island River, Port au Port Bay, western Newfoundland. The dashed line follows the contact between two flows. The steep dip is due to post-Ordovician deformation.

Nature and Distribution of the Ordovician Rocks

Canadian Formations. The Lower Ordovician strata present two strikingly different facies (lithologic expressions), the one of dark shale, rich in graptolites, and the other of dolomite with limy-shelled fossils.

The dark-shale facies occurs to the south of the St. Lawrence River all the way from Gaspé to Quebec City and thence southward on both



Yale Peabody Museum.

Fig. 95. Characteristic four-branched colonies of the graptolite *Tetragraptus* (*Etagraptus*) on a slab of black shale. Lower Ordovician, western Newfoundland. Natural size.

flanks of the Notre Dame and Green mountains through Vermont and eastern New York to New Jersey. It represents the fine dark mud derived from Appalachia and deposited in quiet, stagnant water along the eastern margin of the Appalachian geosyncline. The presence of the four-branched graptolite genus, *Tetragraptus* (Fig. 95), distinguishes it readily from similar but younger shales, and at the same time shows a close connection with similar deposits of the same age in western Europe.

These dark strata are the *Deepkill shales,* so named for a locality in New York but also widely recognized elsewhere in eastern North America. Throughout eastern Quebec they bear a number of interbedded layers or lenses of limestone breccia that have been the object of much speculation. The limestone fragments are angular and show no bedded arrangement or size sorting, yet their fossils indicate that

some were derived from Lower Cambrian formations, others from Upper Cambrian beds, and the majority from Lower Ordovician formations only a little older than the enclosing shales. Since the fragments are not rounded, they could not have suffered long transportation, and since they were derived from formations of widely different ages, ordinary erosional processes could not have brought them together. In Newfoundland thick and very coarse breccias of this type have been found actually associated with submarine thrust faults where they accumulated as talus or landslide deposits in front of the overthrust masses. Probably the breccias in Quebec also owe their origin to thrust faulting, either on the sea floor or in adjacent Appalachia.

The Deepkill shale is now limited to the country south and east of *Logan's line* and can not now be traced into calcareous deposits of the same age. Immediately to the northwest of this disturbed zone, the Lower Ordovician is well developed but in a dolomite facies that extends down the Appalachian trough from Quebec City through the Champlain Valley into New York and Pennsylvania and thence to Virginia and Alabama. In this trough it ranges from about 1500 to more than 4000 feet thick and is divisible into numerous formations that bear local names. The dolomite is light gray in color and has several peculiarities. At various horizons the beds are mud-cracked, indicating that the sea floor was repeatedly exposed. In many places thin polygons loosened by the desiccation cracks were swept together by returning currents to form lenses of "edgewise conglomerate" (Fig. 96). *Cryptozoön* reefs are very common and widely distributed (Fig. 97), but other fossils are as a rule extremely rare. There is almost no detrital material. Quite clearly it is a marine deposit, yet the water was extremely shallow and the sea floor was frequently exposed over wide areas. Similar deposits in Oklahoma, Texas, and New Mexico indicate a remarkable extent of the same peculiar environment. In the Ozark region, and from there northward into Minnesota, the Canadian formations are likewise predominantly of dolomite and bear abundant *Cryptozoön* deposits.

In the Canadian Rockies both the graptolitic and the dolomitic facies are well shown, the latter represented in the center of the geosyncline by cherty limestone and dolomite (Sarbach formation), which, farther west, near the old shoreline of Cascadia, grade over into gray and black shales (Glenogle formation) carrying the *Tetragraptus* fauna.

Post-Canadian Emergence. Nowhere in North America is there any evidence of transition strata from the Canadian into the Champlainian. There is a complete break here, which means that the whole continent was dry land for a long time. How long can not be told, but the marked difference between the faunas of the Canadian and the Champlainian indicates a considerable lapse of time. It is for this reason that some stratigraphers are inclined to regard the Canadian as a distinct period.

Champlainian Formations. The Middle Ordovician formations generally present a contrast with the rocks below, being mostly limestone and calcareous shale instead of dolomite. However, along the eastern border of the old Appalachian geosyncline they also present a black-shale facies all the way from New York to Alabama. Local names are used for the whole or various parts of this facies in different regions, but they refer to parts of a continuous belt of dark shales that represents the fine mud eroded from Appalachia and deposited near the shore while limestones were forming farther west. This is the lower part of the Martinsburg shale * of the "slate belt" of New Jersey and the central Appalachian region and the equivalent Normanskill and Canajoharie shales of New York.

* Black shales of Lower Ordovician age have also been erroneously embraced in the Martinsburg in places in the central Appalachian region.

G. N. KNAPP.

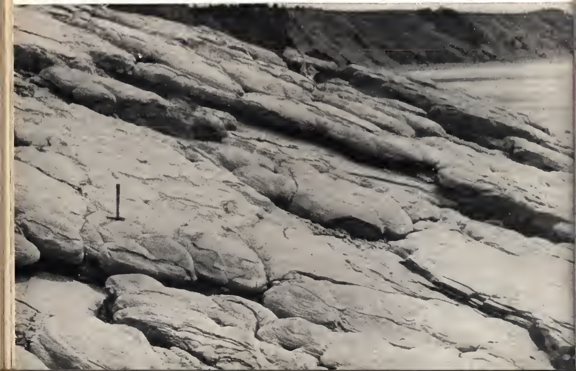
Fig. 96. Edgewise conglomerate, a deposit made of thin chips of mud-cracked layers swept together by the currents after a period of emergence. Deadwood formation (Upper Cambrian), Black Hills, South Dakota.

Between Albany and Utica, New York, the bluffs of the Mohawk Valley show a complete lateral gradation of black shale (Canajoharie) into the Trenton limestone [5] as represented in Fig. 98. To the south in the Appalachian trough the same relation exists between the lower part of the Martinsburg shale and the Mid-Ordovician limestones farther west. Since the shales and the limestone interfinger in a broad transition zone, it is evident that they are of the same age and were formed in an open seaway with no barrier between, the mud settling near shore and the purer, limy sediment farther out. It is interesting to note that the upper shales spread more and more to the west at the expense of the limestone. This reflects the fact that Appalachia was already beginning to rise in Middle Ordovician time and was being stripped of its old mantle, which was being carried into the Appalachian seaway in ever-increasing volume.

West of this shale belt the Middle Ordovician is generally limestone throughout eastern United States, tending to pass locally into dolomite in the upper Mississippi Valley. Two groups are widely recog-

CARL O. DUNBAR.

Fig. 97. Surface of a Cryptozoön reef in the Lower Ordovician dolomite near Port au Port, western Newfoundland. The beds have been tilted to the right by post-Ordovician deformation.



nized, the older (Chazyan) being named for classical exposures in the Champlain Valley of New York, and the younger (Mohawkian) for the extensive display along the Mohawk Valley.

Cincinnatian Formations. Throughout eastern United States the Upper Ordovician formations show a further change from limestone to shales and sandstone, reflecting the progressive uplift in Appalachia. At the beginning of the epoch mud swept westward as far as Cin-

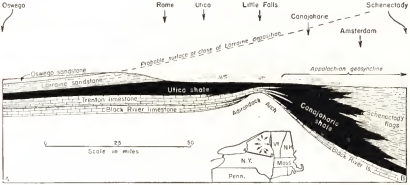


Fig. 98. Idealized section across central eastern New York, showing changes of facies in the Middle and Upper Ordovician formations resulting from the growing uplift in Appalachia. At this latitude a now-buried extension of the Adirondack arch formed a threshold for a time between the Appalachian geosyncline and the shallow sea floor farther west. This ridge was later submerged, and dark muds then spread far to the west. As Appalachia continued to rise, sands also spread farther and farther, reaching west of Oswego late in the period. Vertical scale greatly exaggerated. Data from papers by Marshall Kay.

cinnati, forming black shales in the Appalachian trough and bluish calcareous shales farther west. While shales and thin-bedded limestone continued to form in the longitude of Cincinnati, the sediments to the east became coarser and coarser, finally passing into conglomerates and nonmarine sandstones.

The Queenston Delta. These higher Ordovician sediments of New York and Pennsylvania represent part of a large delta formed on the west side of Appalachia, as shown in Fig. 99. During the first half of the epoch the landward part of the delta was very small, and the sediments were largely, if not entirely, marine. As erosion increased in rising Appalachia, however, the shoreline was crowded gradually westward until a low delta plain stretched from the foothills to beyond the region of Niagara. As the region of deposition was slowly subsiding, sediments accumulated over the landward front of the delta

as well as over its submerged portion. Those in the former region, under the climatic environment then obtaining, were largely oxidized to a red color, while the submarine sediments remained gray. Thus the barren, red Queenston shales (now exposed in the base of the lower gorge of Niagara) are contemporaneous with fossiliferous Richmond beds of the Lake Huron and Cincinnati regions. Irregular subsidence and building at the delta front caused a to-and-fro migra-

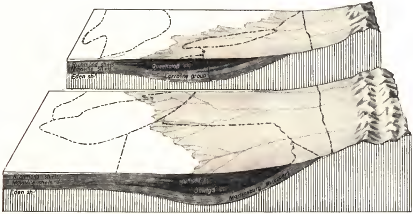


Fig. 99. Stereogram of the Queenston delta as it would have appeared at the close of the Ordovician period. The view is north across Pennsylvania and New York states and the eastern Great Lakes. A part of the old Taconian highland is shown at the extreme right. The block has been parted along an east-west cut, and the names of the chief Middle and Late Ordovician formations are indicated on the vertical faces exposed. In these sections the nonmarine deposits are in darker shading than their marine equivalents. Length of front face, about 600 miles.

tion of the shoreline as the deposits grew, and as a result the Queenston and Richmond formations interfinger over a broad transition zone in Ontario.

Dolomites of the Cordilleran and Arctic Regions. Beyond the limits reached by the sediments from Appalachia, the seas were generally clear, for the western lands remained low. As a result, the Upper Ordovician is represented throughout the Rocky Mountain region and arctic Canada by a remarkably widespread and homogeneous formation of massive, cliff-forming dolomite. In the northern Rockies of the United States, this is known as the Bighorn dolomite. It is recognized under local names from northern Mexico to Alaska and northwestern Greenland, and, strangely, over this vast area it seldom exceeds a thickness of 300 feet. Its fauna is everywhere much the same, consisting of corals, cephalopods, and large gastropods.

Mineral Resources

Petroleum and Natural Gas. The discovery of petroleum, just before the days of the Civil War, marked the beginning of an industry that was destined to change the course of civilization, for it led to the perfection of the internal-combustion engine and made feasible the automobile, the airplane, and other miracles of our modern age.

The first oil well was driven in Devonian rocks in Pennsylvania in 1859, and Ohio followed with a "pioneer well" in 1883 that tapped the Trenton limestone at a depth of more than 1000 feet and produced a heavy flow of gas. This was followed by the rapid exploitation of a large oil field on the Wabash arch in northwestern Ohio (Lima field) that derived both oil and gas from Middle Ordovician strata. Between the years 1886 and 1900 it was one of the major American oil fields; later the production greatly declined, and for some years Ordovician rocks were not important producers.

Since 1920 the Ordovician rocks under the Mid-Continent oil fields have assumed great importance in Oklahoma and northern Texas. The earlier production in this region had been from younger strata, chiefly Pennsylvanian, but with deeper drilling the Wilcox sand of Ordovician age has proved to be the greatest producer in the region, and in several fields, such as that of the Oklahoma City pool, has given rise to spectacular gushers and phenomenal production.

Building Stone. Most of the *slate* produced in America comes from the great shale belt of Ordovician rocks discussed above. The fine muds spread here in Ordovician time were in places so squeezed and metamorphosed by later disturbances that they developed a perfect slaty cleavage. The thicker and more homogeneous beds are quarried and split into shingles for roofing or slabs for electrical switchboards or for other industrial uses. A very large proportion (about 80 per cent) of the material quarried is not suitable for the market, and the mountainous piles of refuse in the slate belt form an imposing monument to the industry. The chief producing states are Pennsylvania, Vermont, New York, and Virginia. In 1939 more than 531,380 tons of slate were produced, with a market value in excess of \$6,680,000. More than nine-tenths of this slate was of Ordovician age. During the war years the use of roofing slate declined, but industrial uses increased, the total value in 1945 being over \$5,658,000.

Limestones and *dolomites* of Ordovician and Late Cambrian age, widely spread in the great Appalachian Valley, serve so many uses

that their aggregate value would be difficult to estimate. Besides furnishing constructional stone for local use, they are crushed for road metal, burnt for lime to use as fertilizer, whitewash, or mortar, used for flux in the reduction of iron ores, or mixed with shales in the manufacture of cement.

It is a striking fact that most of the *marble* quarried in the United States for interior decoration and finish trim is of Ordovician age.

C. R. Longwell.

FIG. 100. Entrance to a marble quarry at Proctor, Vermont. Similar quarries in this region follow steeply dipping beds of pure marble to depths as great as 300 feet. The age of this marble is early Middle Ordovician (Chazyan).

The greatest quarries are near Rutland, in south-central Vermont, where immense underground mines produce most of the "American Carrara" (Figs. 100, 101). Although the stone is of Ordovician age, its metamorphism from limestone to marble was accomplished by orogeny that came later. Pink and deep red "marbles" for decorative interior finish are secured from the Middle Ordovician of eastern Tennessee, and black "marble" is quarried from nearly equivalent rocks on Isle Lamotte in Lake Champlain. Very fine marble is also quarried from Ordovician rocks near Yule, Colorado. The annual production of the Ordovician marbles in normal prewar years exceeded $5,000,000 in value.

Ore Deposits. No important metalliferous deposits of Ordovician age are known in America except the sedimentary iron ore of Belle Isle in eastern Newfoundland. Here the Lower Ordovician strata include six zones of red oölitic hematite that range from a few inches to 50 feet in thickness. The mines now extend under the sea. The annual output averages over 1,000,000 tons.

Lead and zinc ores occur in the Middle Ordovician dolomite in Wisconsin and northwestern Illinois, but since they were formed dur-

Vermont Marble Company.

Fig. 101. Arlington Memorial Amphitheatre in the national cemetery near Washington, D. C., the world's largest cemetery monument, constructed of Vermont marble.

ing a later geologic age, they hardly deserve discussion in the history of this period.

Life of Ordovician Time

Primitive Fishes, a Prophecy of Higher Types of Life. The shallow seas remained the chief arena of life as another geologic period stretched to a close, for the Ordovician has yielded no proved record of either land animals or land plants. At three widely spaced localities in the Cordilleran region, however, middle Champlainian * rocks bear the petrified bony armor plates of very primitive fishes. The first

* Although long regarded as Middle Ordovician (Black River) (Kirk, 1930), this horizon may prove to be of Late Ordovician (Richmond) age. Further investigation is needed.

locality to be discovered is in the Harding sandstone near Canyon City, Colorado, whence Walcott announced the finding of fish remains in 1891. The same horizon has since yielded similar fossils in the Big Horn Mountains and in the Black Hills. In all three localities the bony plates are very fragmentary and show little of the size or character of their owners, but a comparison with well-preserved remains found elsewhere in Late Silurian and Devonian rocks shows clearly that they represent the order of fishes known as the *Ostracodermi* (Figs. 102 and 103). Strange as these fish look, they are yet related to living hagfishes (cyclostomes). From their fragmental nature and their occurrence in cross-bedded sandstone, it seems probable that they inhabited fresh waters, and after death were drifted by the rivers and broken up before arriving in the marine sediments of the littoral zone. As the most ancient relic of vertebrate life they foretell the coming dominance of higher animals—a prophecy that had to wait another geologic period for its fulfilment!

W. L. Bryant.

FIG. 102. Fragment of the bony armor plate of the oldest known fish, *Astraspis desiderata*, from the Harding sandstone at Canyon City, Colorado. Natural size.

Continued Dominance of Marine Invertebrates. The shallow marine waters of Ordovician times swarmed with a rich variety of invertebrate animals. Although the stocks represented in the Cambrian still held the field, a number of new classes sprang rapidly into prominence, notably the graptolites, true corals, crinoids, bryozoa, and clams.

The dolomites so widely formed during Early Ordovician time lost the majority of their fossils during deposition as a result of the diagenetic change from calcareous to dolomitic sediment. In the dolomites the fossils most commonly seen are thick-shelled gastropods and cephalopods and *Cryptozoön* algal reefs.

The widespread, limy formations of the Middle Ordovician contain a more complete record of contemporaneous life than any other group of the Paleozoic rocks. More than 2600 species are known from the Champlainian rocks of North America alone. The host of bryozoans,

limy-shelled brachiopods, and crinoids leaves a striking impress on these faunas. Cephalopods and trilobites still held a prominent position, and the first true corals made their appearance. During this epoch a straight-shelled cephalopod, *Endoceras proteiforme*, attained the greatest size of any creature of the early Paleozoic world, its chambered shell exceeding a length of 15 feet with a diameter at the front of about 10 inches (Fig. 104).

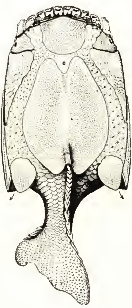


FIG. 103. An ostracoderm fish, *Drepanaspis gemündenensis*, from the Lower Devonian of Germany. Length, about 9 inches. The Ordovician genus, *Astraspis*, is believed to have resembled this Devonian fish. From Patten.

The Upper Ordovician faunas resemble those of the Champlainian in general features, though they are neither so prolific nor so abundant in the muddy and sandy formations of the Appalachian trough nor in the dolomites of the West and the North. In the Cincinnati region, however, the profusion and wonderful preservation of the Late Ordovician life have been an inspiration to amateur collectors and professional geologists as well.

Geographical Restrictions of the Faunas. *Faunal realms* and *provinces* existed in Ordovician time as in the Cambrian or the Present, each of the oceans having certain genera and species of its own, notwithstanding a world-wide similarity in the types of life. It is possible thus to distinguish embayments of Atlantic, Arctic, or Pacific source. Some of the faunas of extreme eastern North America likewise show much closer affinity to faunas of Europe than to those of interior North America, which were closer geographically but occupied a distinct embayment. Of course, when the interior seas became as extensive as they were in Middle and Late Ordovician time, the animals from different provinces could migrate and mingle freely until the faunas became nearly cosmopolitan.

Another type of faunal restriction is seen in the striking contrast between contemporaneous faunas of black shale and limestone. The black shales are the deposits of foul, stagnant mud bottoms upon which but few types of animals could live. As a result their fossils are chiefly the floating graptolites, along with small phosphatic brachio-

pods (Neotremata) which may have been attached to seaweed, the mud-loving brachiopod *Lingula*, and the chambered shells of cephalopods which probably floated after death. Certain types of trilobites are also abundant. On the other hand, we find here none of the corals, bryozoa, limy-shelled brachiopods, clams, or gastropods which dwelled of necessity upon a solider and cleaner sea floor and which made up the faunas now preserved in the limestones and calcareous shales.

Chicago Natural History Museum.

FIG. 104. An Ordovician sea beach, on which specimens of the great cephalopod, *Endoceras*, are stranded. From a painting by Charles R. Knight.

This should not be surprising, for the modern sea floors show equally marked local faunas separated only by differences in the bottom environment. The Bay of Naples, for example, includes a limy shoal known as "Pigeon Bank" which is surrounded by slightly deeper water with a soft mud bottom. Here there are known 341 species of shell-bearing invertebrates (capable of fossilization) of which 296 are restricted to the limy shoal and 31 to the mud bottom. An additional 14 species live on both.[6] A group of animals adapted thus to life on a restricted type of sea floor will, of course, be limited to a distinct type or facies of the sediments and is therefore known as a *facies fauna*. It is evident that the fauna of a Lower Ordovician black shale will

show more general resemblance to that of another black shale of Middle or Upper Ordovician age than to a limestone fauna of its own time. Only the interfingering of the faunas and the sediments where one grades laterally into the other will show the equivalence of dissimilar but contemporaneous facies faunas.

Résumé of the Invertebrate Hosts. Neither Protozoa nor sponges are important in the Ordovician rocks, though both are represented.

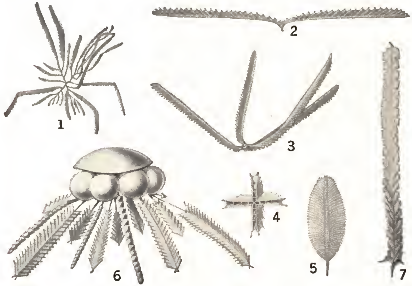


FIG. 105. Ordovician graptolites. 1, *Clonograptus flexilis*, a colony of many branches; 2, *Didymograptus nitidus*, a two-branched colony; 3, *Tetragraptus serra*, a four-branched colony; 4, 5, *Phyllograptus typus*, cross-section of one colony and side view of another flattened in the shales; 6, *Diplograptus pristis*, a colony with floating bell and reproductive pouches; 7, *Climacograptus modestus* (lower part normal, upper flattened). Natural size.

The most distinctive animals of the time were the *graptolites*, which became immensely common at the very beginning of the period (Fig. 105). The majority of these were floating creatures, and therefore of world-wide distribution, drifting freely across the open oceans. *Phyllograptus* and *Tetragraptus*, the distinctive genera of the Lower Ordovician black shales, have been found in Canada, the United States, Scandinavia, Wales, Belgium, France, Peru, Bolivia, Australia, and New Zealand. Successive zones characterized by different generic types are of widespread occurrence and form one of our most exact means of determining the equivalence of rocks in widely separated regions.

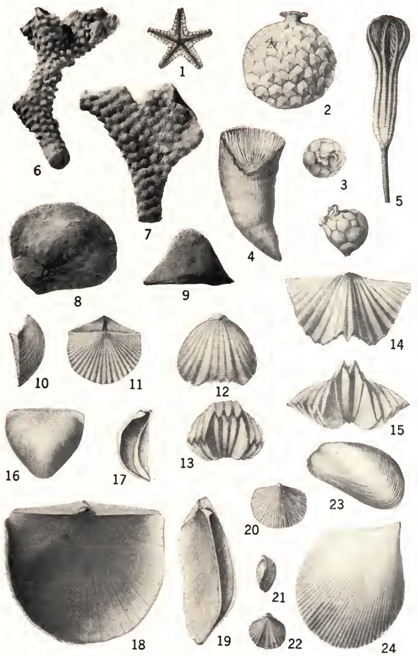


Plate 4. Ordovician Echinoderms (1–3, 5), Coral (4), Bryozoa (6–9), Brachiopods (10–22), and Pelecypods (23–24).

Fig. 1, *Hudsonaster narrawayi*, one of the oldest known starfish; 2, 3, the cystoids *Echinosphærites aurantium* and *Malocystites emmonsi* (upper and side views); 4, *Streptelasma rusticum;* 5, the crinoid *Ectenocrinus grandis;* 6, *Hallopora ramosa* (fragment of a stemlike colony); 7, *Constellaria florida;* 8, 9, *Prasopora simulatrix* (summit and lateral views); 10, 11, *Hesperorthis tricenaria;* 12, 13, *Rhynchotrema capax;* 14, 15, *Platystrophia laticosta;* 16, 17, *Strophomena nutans;* 18, 19, *Rafinesquina alternata* (19, section to show flat living chamber); 20, *Resserella meeki;* 21, 22, *Zygospira modesta;* 23, *Modiolopsis concentrica;* 24, *Byssonychia radiata.* All natural size.

True *corals* appeared near the very base of the Middle Ordovician series. A primitive honeycomb (*Lamottia*) formed low reefs as much as 100 feet across, now shown in the Chazy limestone on Isle Lamotte in Lake Champlain. A small, simple horn coral (*Lambeophyllum*) occurs a little higher, associated with small heads of a compound coral (*Foerstephyllum*). There are but a few species, however, though small reefs are widely distributed in the Late Ordovician strata.

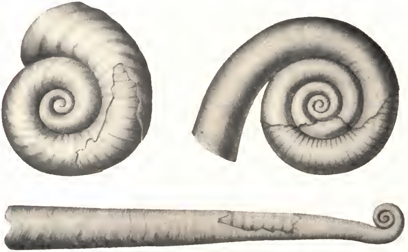


FIG. 106. Ordovician cephalopods. Upper left, *Plectoceras occidentale;* upper right, *Schroederoceras eatoni;* lower, *Lituites lituus.* In each specimen a part of the shell is broken away to show the sutures on the internal mold. Natural size.

Bryozoa (Pl. 4, figs. 6–9) made their first appearance near the base of the Ordovician but expanded into great variety in the middle and upper part of the system. Probably 1000 kinds are present in the rocks of the Champlainian series alone.

Brachiopods (Pl. 4, figs. 10–22) likewise experienced a rapid evolution, especially those with limy shells, though the primitive types with corneous or phosphatic shells which had been so prominent in the Cambrian declined rapidly. The majority of the brachiopods were now "square-shouldered" and almost all had radially striate or ribbed shells. Only a very few had calcareous gill supports in the form of spiralia.

Echinoderms were represented by a variety of *cystoids* and by numerous *crinoids,* along with the first rare *starfish* and the earliest known *blastoids* (Protoblastoidea) (Pl. 4, figs. 1–3,5).

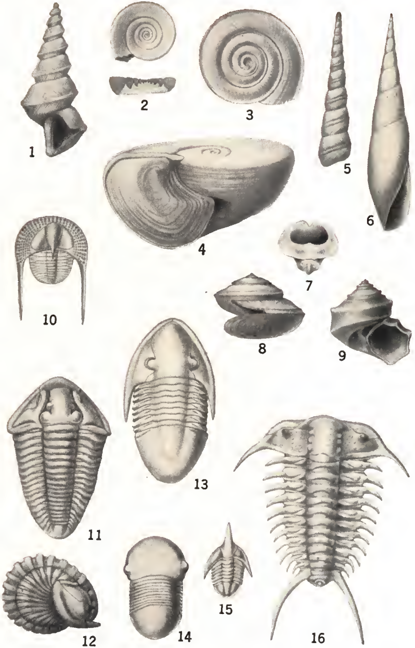


Plate 5. Ordovician Gastropods (1–9) and Trilobites (10–16).

Fig. 1, *Lophospira bowdeni;* 2, *Lecanospira compacta;* 3, *Ophileta grandis;* 4, *Maclurites logani* (with operculum); 5, *Hormotoma artemesia;* 6, *Subulites canadensis;* 7, *Bellerophon troosti;* 8, *Eotomaria supracingulata;* 9, *Trochonema umbilicatum;* 10, *Cryptolithus tessellatus;* 11, 12, *Calymene meeki* (dorsal view in crawling position, and side view enrolled); 13, *Isotelus gigas;* 14, *Bumastus trentonensis;* 15, *Ampyx nasutus;* 16, *Ceraurus pleurexanthemus.* All natural size. Drawn by L. S. Douglass.

Gastropods (Pl. 5, figs. 1–9) showed a surprising evolution into probably as many species as there were of brachiopods, though they were as a rule not so abundant individually as the latter, nor so well preserved. Species with low, widely coiled shells greatly predominated, but many had already attained high graceful spires.

Clams are exceedingly rare until we come to the Champlainian and are first abundant and widely spread in the sandy formations of the Upper Ordovician of the Appalachian trough (Pl. 4, figs. 23–24).

Cephalopods (Figs. 104, 106) are represented by both straight and loosely coiled shells in great variety, the former including a number of species of large size. As a class, these were the largest invertebrates of their time.

FIG. 107. Ostracods on the surface of a slab of Middle Ordovician limestone. About 3/5 natural size.

Trilobites (Pl. 5, figs. 10–16) were still exceedingly numerous and varied, probably attaining the climax of their evolution during this period. If we may judge by their varied form, they were adapted to a wide range of conditions. One striking trend of the times is seen in two of the commonest families, which tended to lose the trilobation of their carapace and the marks of segmentation in both head and tail shields, giving rise to "bald-headed" types like *Bumastus* and *Isotelus* (Pl. 5, figs. 13, 14). The little groveler, *Cryptolithus,* with its pitted frill (Pl. 5, fig. 10), is very characteristic of Ordovician time.

Finally, we must note the first occurrence of the *Ostracoda,* minute crustaceans with bean-shaped, bivalved shells completely enclosing the body as do those of small clams (Fig. 107).

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Chapter 9

THE SILURIAN PERIOD

Founding of the Silurian System. Before 1830 the geologic succession was unknown below the "Old Red" sandstone that underlies the Coal Measures of England. The older rocks were then looked upon as a chaos of deformed and nearly unfossiliferous beds holding little promise that a clear sequence could ever be determined. To their solution there came a remarkable young Scotsman, Roderick Impey Murchison (Fig. 108), whose rise to fame began with his recognition of the Silurian system.

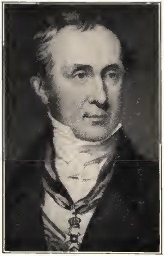


Fig. 108. Sir Roderick Impey Murchison (1792–1871).

After 6 years in public school and 2 at a military academy he joined the army at the age of 15 and served through the Napoleonic wars. With the return of peace he retired to his estate in the northwest highlands of Scotland to become a gentleman of leisure. Fortunately he soon came under the influence of Sir Humphry Davy, who persuaded him to go to London and take courses in chemistry and allied subjects. There the lectures in geology aroused in him an interest that was fanned into enthusiasm as he tramped the hills in company with two of the foremost geologists of the day, William Buckland of Oxford and Adam Sedgwick of Cambridge. At the age of 32 he set himself the task of reading and gaining a self-made education in geology. His spectacular rise from this start to become one of the most distinguished scientists of his time, and, eventually, the director of the Geological Survey of Great Britain, is one of the inspiring chapters in the history of geology.

Murchison's first extensive work was the description of the Silurian system. In 1831 he and Sedgwick resolved to attempt the unraveling

of the "Primitive Series" which lay below the "Old Red" and formed most of the country of Wales. Murchison began his investigations at the base of the Old Red and worked westward (Fig. 109). Here he found that the older rocks, though deformed, were not chaotic but formed a regular succession of gray shales and limestones rich in distinctive fossils. By 1835 he had worked out a succession of thousands of feet of such strata which he defined as a new geologic system.

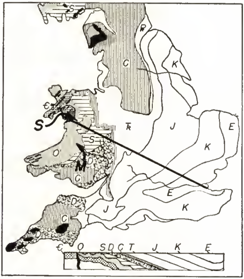


Fig. 109. Geologic map of England and Wales, with cross-section from northwestern Wales to London. Igneous rocks in black. Darts indicate localities where Murchison (M) and Sedgwick (S) began work on the Silurian and Cambrian systems, respectively.

Seeking a classical name, he called it Silurian after an ancient Celtic tribe (the Silures) which Cæsar's legions had encountered here during the Roman conquest. His great volume, *The Silurian System* (1838), is now a classic in geology.

Sedgwick had meanwhile worked out a great sequence of rocks in the much-disturbed region of northwestern Wales (Fig. 109), and this he simultaneously defined as the Cambrian system. In 1835 both Sedgwick and Murchison supposed the Cambrian system to lie entirely below the Silurian, but as work progressed, it became evident that the two overlapped, and that the lower half of the Silurian was included in the Cambrian. When Sedgwick subsequently showed the presence of an important unconformity in the midst of the Silurian,

Murchison still would not yield, but insisted on restricting the name Cambrian to older and generally unfossiliferous rocks. A bitter controversy ensued which not only estranged these two great pioneers but split the geologists of Europe into two camps for more than a generation.

In 1879 Professor Lapworth of Birmingham proposed to cut the Gordian knot by removing the debatable "Lower Silurian" to a distinct system, the *Ordovician,* and after many years of discussion this solution has now received wide acceptance.

Physical History

Patterns of Land and Sea. As the Silurian period opened, Appalachia was still mountainous, but the rest of North America was almost flat. A slow submergence brought shallow seas over much of the eastern United States and over southeastern Canada, as shown in Fig. 110*A*. Notable differences in the Early Silurian faunas of the northern and southern outcrops indicate that a low barrier south of the Great Lakes region separated a southern embayment from a northern one. It is not unlikely that the sea west of Hudson Bay also extended northward to the Arctic (as in Late Ordovician and Middle Silurian epochs), but the evidence for this is not yet clear. No submergence is recorded in the western part of the continent, but it is not improbable that southern Alaska was submerged.

Marked differences between the Early and Mid-Silurian faunas suggest a temporary emergence after this Early Silurian flood, but, if so, the waters returned shortly and spread to still greater extent during the middle of the period (Fig. 110*B*). At this time the eastern part of the continent was again flooded, and embayments entered the western part from the Arctic and the Pacific.

A long and nearly complete emergence ensued during Late Silurian time, when only a shrunken remnant of the inland sea covered a part of the central Appalachian states and the Great Lakes region, as shown in Fig. 110*C*. Thick marine formations accumulated here with immense quantities of salt. This sea must have been connected with the ocean, from which fresh sea water flowed to counterbalance evaporation, but the position of this channel is still uncertain. It may have been via the northeast to the Atlantic or via the northwest to the embayment that covered the Mackenzie Valley region. These possible connections are indicated by broken shading in Fig. 110*C*. No outcrops of Late Silurian rocks are known in either direction, but a line

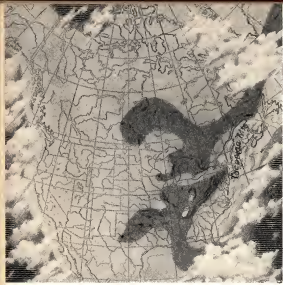


Fig. 110A (left). Early Silurian paleogeography of North America. Land areas lightly shaded; shallow seaways deeply shaded; deep sea horizontally lined; present outcrops solid black.

Fig. 110B (right). Middle Silurian paleogeography. Symbols as above. This shows the maximum Silurian submergence of North America. The Taconian Highlands were now much reduced.

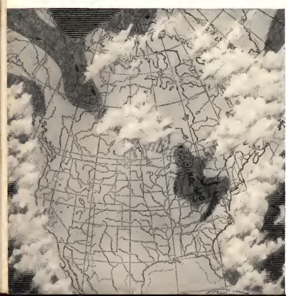


Fig. 110C (left). Late Silurian paleogeography. Symbols as above. Barred strips to the northwest and northeast of the Salina sea represent problematical connections to the oceans; other symbols as above.

of salt seeps along the edge of the Devonian overlap between Lake Manitoba and Great Slave Lake suggests buried salt beds that may be of Late Silurian age.

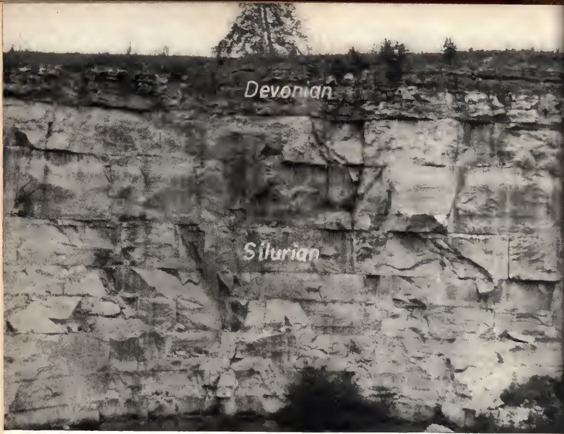
The Silurian period is naturally divided into three epochs: the Early Silurian or Medinan * epoch (named for the Medina sandstone of New York and its correlatives), the Middle Silurian or Niagaran epoch (named for the record so grandly displayed in the gorge at Niagara Falls), and the Late Silurian or Cayugan epoch (named for the thick salt-bearing strata about Cayuga Lake, New York).

The Pacific embayment that covered the panhandle of Alaska left an exceptionally thick series of fossiliferous limestones. These formations, however, have not yet been adequately studied and classified.

Local Volcanic Activity. The northern part of the Appalachian province was again the site of volcanoes which remained active locally during much of Silurian time. Black Cape on the north shore of the Bay of Chaleur, facing the Gulf of St. Lawrence, displays over 4000 feet of black lavas interbedded with Middle Silurian limestones. Apparently the eruptions here were from submarine volcanoes, for the base of the first flow includes fossil coral heads and brachiopods over which the lava flowed. Farther southwest in New Brunswick and especially in southeastern Maine, ash beds and lava flows attain the impressive thickness of 10,000 feet or more. Here and there among these volcanics are strata with marine fossils that prove the Silurian age of the lavas. Lava flows, volcanic breccia, and tuff occur also in the Silurian of southern Alaska and in the Copley formation of probable Silurian age in northern California.[1]

Quiet Close of the Period in America. No mountains were made in North America at the close of this period, and the overlying Devonian formations generally lie parallel to the Silurian with little evidence of hiatus. Outside the central Appalachian trough, however, it is usually the Middle Devonian that rests upon the Middle Silurian, since both the Late Silurian and the Early Devonian formations have a very restricted distribution. The relation at the "Beargrass" quarries near Louisville, Kentucky (Fig. 111), is general over the Ohio Valley, where pure Middle Devonian limestone rests disconformably on similar strata of Middle Silurian age. When viewing such an outcrop, it is difficult to realize that in the Appalachian trough sediments

* General agreement has not yet been reached as to the best name for the Early Silurian epoch. The name Alexandrian is also in use.



CHARLES SCHUCHERT.

Fig. 111. Disconformable contact of Middle Devonian on Middle Silurian limestones in Beargrass quarries near Louisville, Kentucky. The contact is in the midst of the massive bed below the word Devonian.

almost a mile thick were formed during the interval represented here by an irregular bedding plane. Obviously the emergent continent lay quiet and but little above sealevel during the long interval.

Caledonian Disturbance of Europe. In Europe, on the contrary, the close of the Silurian witnessed the rise of the majestic Caledonian Mountains, which ranged northeastward across the British Isles and Scandinavia. In Scandinavia the orogenic forces came from the west, folding the Silurian and older formations and carrying them eastward in a series of great thrusts. Throughout the length of Norway and Sweden, a distance exceeding 1100 miles, the pre-Devonian formations were folded, overturned, and overthrust with eastward movement on individual fault planes as great as 20 to 40 miles. The mountains that crossed Great Britain seem to have been a subparallel range

striking to the west of that in Scandinavia and curiously paired with it, in that here the thrusts were to the west instead of the east. If we include the folding in eastern Greenland and Spitzbergen, the Caledonian Mountains can be traced for more than 4000 miles and were undoubtedly one of the great mountain systems of the world (Fig. 112).

Another range stretched eastward across northern France and southern Germany into northern Austria, while still other mountains were

Fig. 112. Map showing the location of the Caledonian Mountains of late Silurian date.

forming in northern Africa (Oran Sahara) and in north-central Asia (Irkutsk basin of Siberia).

Stratigraphy of the Silurian Formations

Influence of the Taconian Range. During Early and Middle Silurian time the Appalachian trough received abundant sandy sediments from the east as the highlands in Appalachia were gradually worn down. This material, trapped between Appalachia and the Cincinnati arch, kept the geosyncline silted up to near or above sea-level, oscillating between the condition of shallow sea floor and low coastal plain. Along the eastern margin of the geosyncline, pure sandstone and quartz conglomerate stretches all the way from New York to Alabama, attaining a maximum thickness of more than 1000 feet and ranging between this and 500 feet over most of the folded region, where it is one of the chief ridge makers.

To the northwest and west the sandstone grades over into shale, but tongues of it reach far to the west, as indicated in Fig. 113. Along the eastern margin the sandstone is generally unfossiliferous and

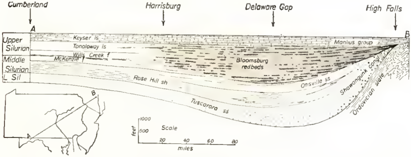


FIG. 113. Section of the Silurian formations between Cumberland, Maryland, and High Falls, New York, showing the influence of the Taconian Range. The section runs obliquely across the geosyncline. Data from papers by C. K. and F. M. Swartz.

may have been deposited upon a low coastal plain, but farther west it includes a limited variety of marine fossils, notably ostracods, small clams, and the burrowing brachiopod, *Lingula*.

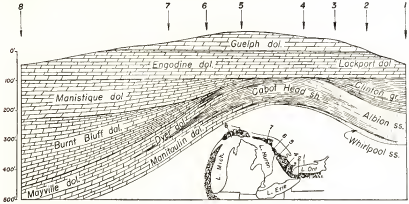


FIG. 114. Silurian section along the Niagara cuesta from Medina, New York, to Manistique, Michigan. The inset map shows the outcrop belt and the position of the eight numbered localities: 1, Medina, New York; 2, Niagara Falls; 3, Hamilton, Ontario; 4, Cataract; 5, Owen Sound; 6, Cabot Head; 7, Manitoulin Island; 8, Manistique, Michigan. Vertical scale greatly exaggerated. Adapted from E. R. Cumings.

During Early Silurian time the sand spread as a vast, continuous sheet over the geosyncline. Several local formation names are used for it (Shawangunk, Medina, Tuscarora, Clinch), but they all refer to

parts of this single vast deposit that records the degradation of the Taconian Range. As shown in Fig. 113, the sand was much more restricted in Middle Silurian time, and from then until nearly the end of the period most of the deposits in the geosyncline were muds. Finally, by Late Silurian time, even muds were more limited, and limestones accumulated over the western half of the geosyncline; as a final episode the sea again spread over the truncated folds along the western edge of the Taconian Range. By this time Appalachia was worn so low that limestone formed as far east as the Hudson Valley (see Figs. 113 and 93).

In Gaspé Peninsula, where the Silurian formations rest unconformably on the metamorphosed and folded Ordovician, the basal Silurian also includes conglomerates and thick sandstones.

Charles Schuchert.

FIG. 115. Cabot Head shale (below) grading upward into Grimsby (=Albion) sandstone, along New York Central Railway in Niagara Gorge. This is a detail of the transition represented in Figs. 114 and 116.

A striking contrast is seen, however, if we journey 70 miles across the Gulf of St. Lawrence to Anticosti Island, where the Late Ordovician and Early Silurian are both represented by flat-lying formations of calcareous shale or limestone. There is no evidence here of the Taconian orogeny, in either the structure or the sediments. Moreover, there are younger Ordovician beds on Anticosti (Gamache formation) than any known elsewhere on the continent, showing that the Ordovician seas lingered longest here. The explanation of this striking contrast in the record of Anticosti Island and Gaspé lies in the fact that Gaspé was originally much farther south and its rocks have been overthrust many miles to the north by a later disturbance, bringing rocks from the eastern part of the geosyncline near those originally deposited far from the Taconian Range.

The westward gradation of the Early Silurian deposits from sandstone into shale and finally into limestone is exceptionally well displayed in nearly continuous exposures that follow the base of the

Niagara cuesta from Rochester, New York, through Niagara Falls and across the Ontario Peninsula into the Manitoulin Islands (Fig. 114).

Middle Silurian Limestones and Coral Reefs. West of the Cincinnati arch even the Early Silurian formations are of limestone. Al-

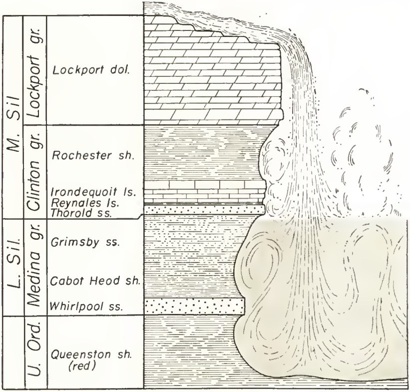


FIG. 116. Silurian section at Niagara Falls. Height of falls, 158 feet; depth of water, 150–200 feet. Section made through Horseshoe Falls. Modified from G. K. Gilbert.

though of considerable areal extent (Fig. 110*A*), they are commonly a few feet or a few tens of feet thick and represent only a small part of this epoch, but it is notable that there were no uplands within adequate reach to supply even muds to this part of the interior sea.

Middle Silurian formations are far more widespread and are considerably thicker, but they, too, are almost entirely made of limestone (locally dolomite in the upper Mississippi Valley). Even where

widely distributed across the Canadian Shield, they are predominantly calcareous.

The grand exposures about Niagara Falls (Fig. 116) display most of the Middle Silurian in its typical development, resting upon the sandy phase of the Lower Silurian (Fig. 115). The lip of the falls is formed by the thick-bedded Lockport dolomite, which also rims the gorge in cliffs more than 100 feet high (Figs. 116 and 117). This resistant formation, overlying the weak shales below, holds up the Niagara cuesta across western New York, the peninsula of Ontario, and the Manitoulin Islands north of Lake Huron. It extends southward under cover of younger formations, to appear again about the flanks of the Cincinnati arch. Large outliers occur farther north in Canada, one of the greatest being along the west shore of Hudson Bay.

The rocks exposed above the brink of the falls and along the upper rapids represent the base of the *Guelph dolomite*. This formation is typically developed only in Ontario and Ohio, where it is characterized by a peculiar fauna of gastropods, a large clam (*Megalomus*), and heavy-shelled, hingeless brachiopods (trimerellids). The Guelph

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Fig. 117. Silurian formations at the lower end of Niagara Gorge above Lewiston. The base of the Silurian is near the middle of the lower wooded slope.

Fig. 118. Small bryozoan reef in the upper limestone (Irondequoit) formation of the Clinton group. Niagara Gorge. The reef is 15 feet across, and its top projects several feet into the overlying Rochester shale.

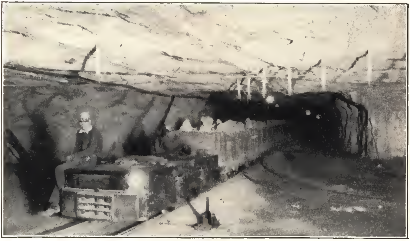
fauna appears not to have reached much to the south of central Ohio. The Lockport limestone grades westward into dolomite, and to the south and west of Lake Michigan is less easily separated from the Guelph, the two forming a thick group of dolomite beds that extends underground into Kansas and Nebraska, cropping out locally in Iowa.

Below the Lockport formation at the falls and in the gorge at Niagara lies the Clinton group, here much thinner than in the Appalachian region and likewise more calcareous.

The Silurian of western North America is not well known but is represented by 1000 feet of dolomite in Idaho and Utah and 1500 feet of similar beds in southern Nevada. Great thicknesses of dolomite are exposed also in British Columbia, the Mackenzie Valley, the Arctic Archipelago, and southern Alaska.

Throughout the extent of the limy Niagaran formations, corals were common and at many places made small reefs. Limestones and dolomites with reef structures occur in the Medinan series but are especially common in the Niagaran of Indiana, northern Illinois, southern Wisconsin, Iowa, and Ontario north at least to Lake Huron. Some of

the oldest of these reefs were made by bryozoans (Fig. 118), but the majority were formed by various kinds of stony corals (Tabulata, Tetracoralla, and hydrocorallines like the stromatoporoids). These reefs vary in size from several feet to more than a mile across, and in height from a few feet up to 75 feet. All are unstratified masses made up of entire or broken skeletons, buried in a matrix of coral sand and mud, the whole more or less altered through diagenesis into either a pure calcium carbonate or a dolomite.



Retsof Mining Company.

Fig. 119. A salt mine in the Upper Silurian at Retsof, central New York. The tunnel is cut in solid rock salt, and the cars are loaded with salt on their way to the shaft.

Although corals were the chief builders, many other groups of animals contributed to these reefs. It is more correct, therefore, to speak of them as organic reefs than as coral reefs. The name *bioherm* (Gr. *bios*, life, + *herma*, reef) has been used for such structures.

Upper Silurian Desert Deposits and Waterlimes. In central New York the salt-bearing shales of the *Salina group,* more than 1000 feet thick, succeed the Niagaran limestone. Here the lower half is composed of bright red unfossiliferous shale (Vernon) and the upper half of gray shale (Camillus) with several beds of rock salt. The salt (Fig. 119) underlies an area measuring 150 miles from east to west and extends southward under southern New York, northern Pennsylvania, and Ohio. Several distinct beds occur at intervals in the shale, individual beds of pure salt reaching a thickness as great as 80 feet. At Ithaca, New York, where the formation lies between 2000 and 3000

feet underground, there are seven beds of salt with an aggregate thickness of 250 feet; but the greatest accumulation of Silurian salt is deeply buried under the center of the Michigan Basin, where deep wells reveal salt beds aggregating 1600 feet in thickness.[2]

Southeastward toward Appalachia the entire series passes into barren redbeds, but southwestward in central Pennsylvania interbedded limestones (Tonoloway) bear abundant marine fossils at many horizons.

After the salt deposition the marine waters again spread widely over the New York desert, and a series of thin but persistent dolomites and waterlimes was left as the final record of the Silurian period. Waterlime is an impure calcareous sediment with a large admixture of silt, possibly the wind-blown dust from the neighboring arid lands; it was once much used in making cement.

Climate

Cosmopolitan Climate of the Middle Silurian. The coral reefs and coral-bearing strata distributed widely throughout the Middle Silurian limestones show that mild temperatures again extended into the arctic region. The evidence lies not so much in the mere existence of the reefs and corals as in the fact that the species are everywhere identical or much alike, whether in Kentucky, New York, the Hudson Bay region, or within the Arctic Circle, as at Polaris Bay, northern Greenland. The wide extent of the limestones and dolomites confirms the evidence of the corals. Other groups of invertebrates, notably the cephalopods, show an equal disregard for latitude. Certain species found in Iowa are clearly migrants from Europe by way of the polar region. Most remarkable of these is the four-sided coral, *Goniophyllum* (Fig. 120), which, unlike all others, had an operculum, or cover, of four limy plates.

Fig. 120. A distinctive Silurian coral, *Goniophyllum*. Natural size.

Late Silurian Deserts. As the continent emerged during Late Silurian time, arid conditions spread over the eastern United States, and a large area including Michigan, Ontario, New York, and Pennsylvania took on the characters of a desert basin. In the midst of this region, a lingering arm of the inland sea shrank to a "dead sea" in

which vast quantities of salt and gypsum were precipitated. The red Vernon shales of the Salina group probably represent the muds of a barren coastal plain, where free access of the air to the soil during long periods of drought kept the enclosed iron thoroughly oxidized. The gray shales, deposited under hypersaline waters, include salt and gypsum at many horizons over an area of nearly 100,000 square

Charles Schuchert.

FIG. 121. Mud-cracked layers of impure limestone in the Upper Silurian (Salina group) at Roundtop, Maryland.

miles. Since the deposition of 1 cubic foot of salt (sodium chloride) would require the evaporation of about 80 cubic feet of normal sea-water, it is clear that severely arid conditions must have persisted here for a very long time. It is not to be inferred that the water was deep, however; there was probably an intermittent inflow of more sea-water from the outer ocean to balance the evaporation and supply the salt. Indeed, the abundant mud cracks in the gray shales (Fig. 121) indicate that wide mud flats were repeatedly exposed.

The cause for the aridity may have lain in the flatness of the extended land mass, which offered no elevations to chill the westerly winds after they had crossed the interior of the continent.

Economic Products

Clinton Iron Ore. The red iron ore mined in the Birmingham region of Alabama now supplies about 10 per cent of the iron produced annually in the United States and is the only important competitor of the Pre-Cambrian ores of the Lake Superior region.

The Silurian ore is an oölite of the red oxide, hematite, occurring in thin, lenticular beds alternating with the gray shales of the Clinton group. The ore locally includes abundant marine fossils and commonly has replaced broken bits of the shells. It was originally deposited as a sedimentary accumulation on the Silurian sea floor. One or more beds of ore can be found at most of the outcrops of the Clinton shales all the way from New York to Alabama, but the thickness is generally only a few inches to a foot or two, rising locally to 3 or 4 feet.

Before the Civil War the Silurian iron was extensively exploited in the region of Clinton, New York, but since the discovery of the vast iron deposits in the Lake Superior region most of the Silurian mines have been driven out of competition. In the vicinity of Birmingham, Alabama, however, the Clinton ore beds reach their maximum development, the "Big Seam" having a thickness of 40 feet, of which 15 to 17 feet is rich enough to be workable. Here, in immediate proximity to the Big Warrior coal field, the ore is profitably and extensively mined. It is estimated that over 600,000,000 tons of this ore are still available underground.

Salt. Salt is another important mineral product of the Silurian rocks. During the years 1943–1945 the average annual production of salt from the Silurian rocks of New York State was in excess of 2,900,000 tons and had a value of nearly $10,000,000. This was slightly less than 20 per cent of all the salt mined in the United States. The salt is obtained chiefly by forcing water down deep drill holes and pumping up the brine to be evaporated and refined; it is also mined and sold in blocks to be used as salt licks for cattle.

Silurian Life

The Continued Reign of Marine Invertebrates. Silurian life was a modification, through lineal descent, of that of the Ordovician, with no drastic innovations. Marine invertebrates still predominated, almost to the exclusion of other forms of life. Some of the invertebrate stocks, however, already showed evidences of decline, whereas others,

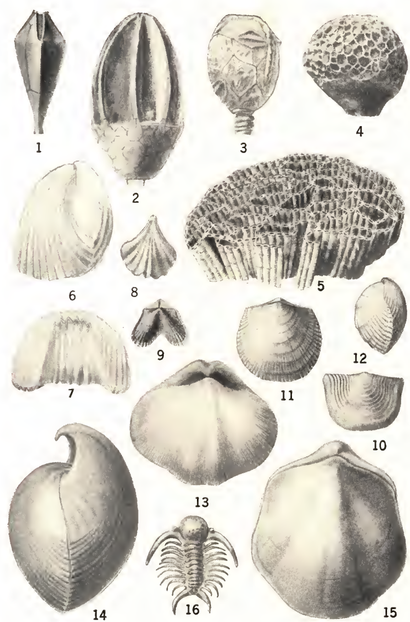


Plate 6. Silurian Blastoid (1), Crinoid (2), Cystoid (3), Corals (4, 5), Brachiopods (6–15), and Trilobite (16).

Fig. 1, *Troostocrinus reinwardti;* 2, *Eucalyptocrinus crassus;* 3, *Lepadocrinites manlius;* 4, *Favosites forbesi*, a honeycomb coral; 5, *Halysites catenularius*, a chain coral; 6, 7, *Uncinulus stricklandi;* 8, *Rhynchotreta americana;* 9, *Bilobites bilobus;* 10, *Leptæna rhomboidalis;* 11, 12, *Atrypa reticularis;* 13, *Eospirifer radiatus;* 14, *Conchidium laqueatum;* 15, *Pentamerus oblongus;* 16, *Deiphon forbesi barrandei.* All natural size. Drawn by R. G. Creadick.

of little importance in the Ordovician, now sprang into prominence.

The *graptolites*, for example, had greatly declined and are found at only a few limited horizons in the American Silurian, though in Europe they were still numerically abundant but mostly of one genus, *Monograptus*.

Corals, on the contrary, showed an extraordinary expansion into many genera and species including honeycombs (*Favosites*), chain corals (*Halysites*), cup corals, and compound types of tetracorals. In the clear Niagaran seas they formed reefs of widespread distribution (Pl. 6, figs. 4, 5).

Bryozoa were still very common and locally made small reefs (Fig. 118).

Brachiopods showed a marked expansion. To the flattish and square-shouldered types were added globular, short-hinged forms with pointed beaks and plicated shells. Spire-bearing types also for the first time became common (Pl. 6, figs. 6–15).

Among the echinoderms, *cystoids* (Pl. 6, fig. 3) were rather common, *blastoids* (Pl. 6, fig. 1) just beginning, *starfish* and *echinoids* exceedingly rare. *Crinoids* (Pl. 6, fig. 2), on the contrary, experienced a remarkable evolution and grew in the greatest profusion, their calcareous plates contributing largely to the limy sediments of the clearer seas. Growing as they did on graceful, slender stems, these "lilies of the sea" undoubtedly furnished the most colorful spots upon the Earth.

The molluscs were generally much less conspicuous than in the preceding period, but in some of the late Niagaran dolomites heavy-shelled *gastropods* are abundant. Nautiloids and clams were both present but hardly noteworthy.

Trilobites had passed their climax but still remained common. A number of types showed a tendency toward bizarre development of spines, which may have been a protective measure against the evolving fishes (Pl. 6, fig. 16).

The *eurypterids*, or "sea scorpions," formed perhaps the most striking and distinctive element in the late Silurian faunas (Figs. 122, 123). They are very localized in their occurrence and practically confined to a few limited horizons, but they are common fossils where they do occur. They were sparingly represented in the Ordovician but in the Silurian rose to a meteoric climax only to decline abruptly in the next period, after which they were very rare. Most of them were small animals from a few inches to a foot or so in length, but a few species attained large dimensions. The largest American species (*Pterygotus buffaloensis*) is found in the Bertie waterlime of western New York, where

fragments of exceptionally large individuals have led to an estimate of a body length of 7 feet or a length of 9 feet over all, with pincers extended. This creature ranks as the greatest arthropod of all time.

Ostracods continued in great abundance, and some species now attained a relatively large size, the greatest, however, scarcely reaching a length of 1 inch.

Fishes. Fishes undoubtedly lived in the streams throughout this period, but their remains are exceedingly rare, consisting essentially of

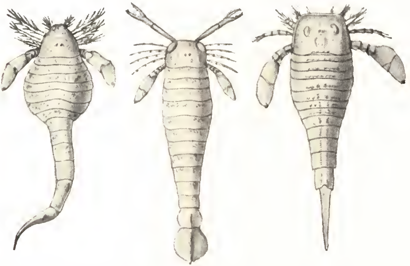


FIG. 122. Three characteristic types of eurypterids. Left, *Eusarcus scorpionis*, $\times \frac{1}{2}$; center, *Pterygotus buffaloensis*, $\times \frac{1}{25}$; right, *Eurypterus remipes*, $\times \frac{1}{3}$. After Clarke and Ruedemann.

small, bony tubercles and armor plates which studded the skin of certain of the primitive Ostracodermi in lieu of scales. In the highest Silurian beds of Norway,† however, remarkably preserved but very primitive fishes (Fig. 124) have been found in abundance.[3] These have no well-defined jaws, and in this and other primitive characters they appear to be ancestral to the modern hagfish or cyclostome.

Beginnings of Terrestrial Life. Fragments of supposed *land plants* have been described from the Silurian rocks of Gotland, England, and Australia. The remains are few, however, and very frag-

† The Silurian age of these beds is not beyond question. Similar beds constituting the typical Downtonian of Scotland are now referred to the basal Devonian.

FIG. 123. Reconstruction of eurypterids on a Silurian sea floor. After Ruedemann. About $\frac{1}{10}$ natural size.

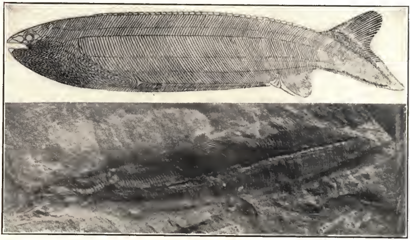


FIG. 124. A primitive fish (*Pharyngolepis oblongus*) from the uppermost Silurian (Downtonian beds) of Norway. Above, a reconstruction; below, dorsal view of a specimen in the rock. After Kiaer. About $\frac{2}{3}$ natural size.

mentary, consisting of bits of stems some pieces of which bear small, bractlike leaves. One of the Australian types bears slender leaves 2 centimeters long and 1 millimeter broad. Some of the stems described as land plants may be those of marine algæ.

"These Silurian fossils are the oldest examples of what appear to be terrestrial plants. . . . They do not tell us very much; but they afford evidence of two Silurian types, probably terrestrial, which agree closely with forms characteristic of the earlier Devonian floras and of a third type that appears to be peculiar to this meagre Pre-Devonian flora."[4] Soft-tissued algæ and fungi may have been abundant in regions of sufficient moisture and suitable climate.

Possibly the *first air-breathing animals* were *scorpions* and *millipeds*, both of which have been found rarely in the Upper Silurian rocks. These first-known scorpions are small creatures, not over 2½ inches long, and their resemblance to modern scorpions is striking. Nevertheless they may still have been aquatic animals. They are almost certainly descendants of the eurypterids, which were aquatic, and none of the fossil specimens has revealed the respiratory structures that would prove whether they breathed air or water.

The millipeds have been found only in Wales, where they are associated with eurypterids.

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[3] *The Downtonian Fauna of Norway, I, Anaspida;* by J. Kiaer. Vidensk.-Skrifter, I. Mat.-Naturw. Klasse, 1924, No. 6.

[4] *Plant Life through the Ages;* by A. C. Seward. The Macmillan Co., New York, 1931, p. 110.

Collateral Reading

Niagara Falls Folio; by E. M. Kindle and F. B. Taylor. U. S. Geological Survey, Geologic Folio 190, 1913.

Treats of the classic section of Silurian formations exposed in the Niagara Falls region.

The Founders of Geology; by Sir Archibald Geikie. Macmillan and Co., London, 1905, pp. 412–434.

An interesting account of the founding of the Silurian, Cambrian, and Devonian systems.

Chapter 10

THE DEVONIAN PERIOD

Discovery of the Devonian System. In Great Britain, where historical geology had many of its first devotees and the Early Paleozoic systems were named, the Coal Measures are underlain by a great succession of sandstones and shales known to the pioneer geologists as the "Old Red Sandstone." Until Murchison and Sedgwick had defined the Silurian and Cambrian systems, it formed the base of the determined geologic column, and thereafter it was given a place between the Silurian and the Carboniferous.

In 1836 Murchison and Sedgwick began to work in Devonshire and Cornwall, the southwestern provinces of England, which had long been known to be largely covered by a series of gray rocks considered to be Carboniferous because of the presence of fossil plants. They found that only the upper part of these rocks is plant-bearing; the lower part they referred to the Cambrian solely because it was badly deformed and in that respect resembled the rocks of northwest Wales. However, when fossil corals found by local collectors were submitted to the paleontologist Lonsdale, he found them intermediate between corals of the Silurian and those of the Carboniferous, and suggested that these beds might belong to the "Old Red." Murchison and Sedgwick were hard to convince, but after 2 years they accepted Lonsdale's view and proposed the name Devonian for a new system between the Silurian and the Carboniferous. In it they embraced these marine deposits of Devonshire, the Old Red sandstone, and correlative formations elsewhere.

It was eventually found that in Devonshire the system is 10,000 to 12,000 feet thick and consists of graywacke, slates, and limestone, associated with lavas and tuff. The region was an unfortunate one on which to base a system, for the beds are so disturbed by folding, faulting, and intrusions that the detailed succession is still not wholly known. Equivalent but less-disturbed beds had already been described in the Rhine Valley in Germany, and these became the actual standard or type section of the system in Europe. A still finer section in New York State is the standard of reference for America.

Physical History of North America

The Devonian Cycle of Submergence. Although the close of the Silurian left Europe rugged and mountainous, North America remained low and flat. The Devonian submergence began in the Appalachian trough, which was soon transformed into a narrow strait reaching from Newfoundland to Mississippi and at times separating Appalachia completely from the mainland (Fig. 125*A*). No marine deposits of Early Devonian time are known in the Cordilleran trough, but a fresh-water formation bearing fossil fish and land plants is present at Beartooth Butte in Wyoming. During this epoch, probably less than 5 per cent of the present continent was submerged.

The beginning of Middle Devonian time was marked by submergence that spread the Appalachian seaway westward to the Mississippi Valley, and soon brought another vast arctic flood creeping southward across western Canada by way of the Mackenzie Valley region in a seaway nearly 1000 miles wide. This joined the embayment that then occupied the Cordilleran trough in Utah and Nevada. From this time until late in the period the two great geosynclines were more or less persistently submerged and received a great thickness of sediments; but the Central States were barely awash, or slightly emergent, during much of the time. The middle and lower maps of Fig. 125 represent maximum submergences, but should be considered only temporary stages in an ever-changing scene. Possibly 40 per cent of the present continent was submerged at one time or another during both the Middle and Late Devonian epochs, but toward the close of the period emergence was gradual and finally complete.

The Acadian Disturbance. About the middle of the period, uplift was renewed in Appalachia, and the geosyncline was more rapidly depressed. These movements continued with increasing intensity until the close of the period and culminated in the formation of a bold mountain chain that followed the axis of old Appalachia down through the Maritime Provinces of Canada and the New England states and thence southward to about the latitude of Cape Hatteras (Fig. 125*C*). This orogeny was first recognized in the Maritime Provinces—the Land of Acadia—and for this reason it has been named the *Acadian disturbance.*

The Acadian Mountains were a second generation of Appalachians, much like the Taconian Range of the Late Ordovician and involving

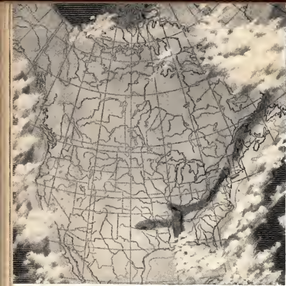


Fig. 125A (left). Early Devonian (Helderbergian) paleogeography. Land areas lightly shaded; shallow seas deeply shaded; deep sea horizontally lined; present outcrops solid black.

Fig. 125B (right). Middle Devonian paleogeography. Lined shading in Appalachian region marks the subaerial part of the Catskill delta; other symbols as above. This map shows the maximum spread of the early Hamilton seaways. The western sea is based on the Stringocephalus fauna.

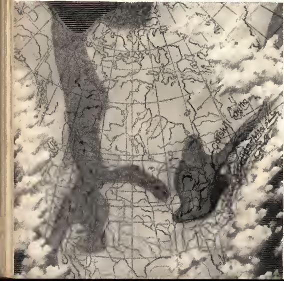


Fig. 125C (left). Late Devonian paleogeography. Symbols as above. This represents the maximum submergence of the epoch, during the Chemung age. Note the rising Acadian range bordered by the growing Catskill delta.

nearly the same region. In Acadia, as in New England, the Devonian and older sedimentary formations of the geosyncline were strongly folded and much disturbed by igneous intrusion. The effect was both profound and permanent, uplifting and folding all the rocks in this part of the Appalachian trough and destroying its geosynclinal nature so that the seas never again traversed it.

From New England south, the disturbance was east of the present fold belt, in the area of the Piedmont and the Coastal Plain and probably that of the continental shelf. Although the sedimentary rocks have since been destroyed here, and details of the Acadian orogeny can not be restored, the Devonian formations still preserved in the geosyncline indicate the presence of marked highlands at least as far south as Cape Hatteras.

The volume of the sediments derived from the erosion of Appalachia and preserved in the geosyncline gives some measure of the uplift. The detrital Devonian formations from New York to Virginia, inclusive, have been estimated to measure some 63,000 cubic miles. This is approximately the volume of the modern Sierra Nevada, which exceed 75 miles in width, are 400 miles in length, and rise to nearly 3 miles above sealevel along their crest. Since the deposits laid down in the geosyncline were all derived from the western slope of the Acadian mountains, it is clear that Appalachia was much more than 100 miles wide or was very lofty or was continuously uplifted during erosion.

The above estimate does not include the deposits in Acadia or those originally laid down along the mountain front between Acadia and New York and subsequently eroded away.

While the Catskill delta (see p. 206) was forming in New York, a similar great delta was building in Gaspé, and its nonmarine beds near Escuminac, at the head of Chaleur Bay, have yielded land plants and many fishes, including the probable forerunner of land vertebrates (Figs. 138, 139).

Igneous Activity. Much igneous activity accompanied the Acadian disturbance. Great thicknesses of bedded lavas and tuffs in southern Quebec, Gaspé, New Brunswick, and Maine record volcanoes that were active during Devonian time. In most of New England and parts of New Brunswick such extrusives have been largely eroded away, exposing the related deep-seated plutonic rocks.

The granite core of the White Mountains is an example. Here the intrusions began during the middle of the period and were renewed on a larger scale as the Acadian disturbance came to its climax.[1]

Other Devonian batholiths are the granites at St. George and in the Little Megantic Mountains of New Brunswick,[2] the granites that make up most of Nova Scotia, and those that form the cores of such monadnocks as Mt. Katahdin in Maine. The great pegmatites of Connecticut are also largely of Devonian age, according to the lead-uranium ratios of their radioactive minerals.

Growth of the Catskill Delta. As the Acadian mountains rose, erosion was greatly stimulated, and the streams flowing westward into the geosyncline built out a vast compound delta in New York and Pennsylvania. The exposed surface of the delta was small in Middle

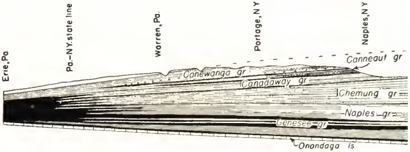


FIG. 126. Cross-section of the Catskill delta, from Erie, Pennsylvania, to the Catskill lines indicate the inferred original extent of the beds which have since been partially careous shales in close parallel lines. This section is fully exposed along the northern edge

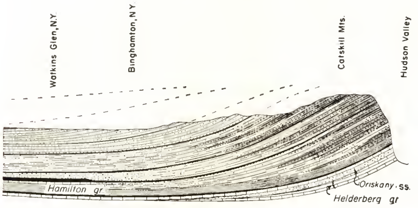
Devonian time but increased steadily during the later part of the period until it became a great alluvial plain more than 100 miles wide, sloping down from the foothills of Appalachia to the inland sea. As the region slowly subsided, layer after layer of detrital sediment was spread over it, building up the thick deposit of sandstones, conglomerates, and shales from which the modern Catskill Mountains have been carved. The Catskill delta was named for these exposures. The terrestrial part of the delta is distinctly shaded in Fig. 125*B*. A cross-section is shown in Fig. 126.

STRATIGRAPHY OF THE AMERICAN DEVONIAN [3]

Appalachian Province. The Devonian system is exceptionally developed in Pennsylvania and southern New York, where, fortunately, the natural exposures permit its study in three dimensions. Magnificent exposures in the fold belt follow the axis of the old Appalachian trough, where Devonian beds are 12,000 to 15,000 feet thick,

and the northern edge of the Allegheny Plateau in southern New York presents a cross-section nearly at right angles to the trough. This area is probably unsurpassed as a clear display of the facies changes that are produced in geosynclinal deposits by the growth of mountains in the bordering land. The relations are shown in Fig. 126.

The Lower Devonian formations are relatively thin and are limited to the axis of the geosyncline. Two stages are recognized, the *Helder-*



Mountains. Section about 250 miles long; vertical scale greatly exaggerated. The broken
eroded away. Redbeds are shaded, black shales are shown in solid black, and gray cal-
of the Allegheny Plateau. Data from Chadwick and Cooper.

bergian and the *Deerparkian,* each with several formations. The Helderberg stage includes only limestones and calcareous shales, and this shows clearly that near-by Appalachia was then so low that it supplied only fine mud and even that in small volume.

The Deerpark stage is represented here chiefly by the *Oriskany sandstone,* a remarkable formation of nearly pure quartz sand with a calcareous matrix. Its distribution is peculiar, being limited to the eastern part of the geosyncline in the Appalachian region, and then reappearing along the Mohawk Valley and extending westward to Mackinac Straits in Michigan. The sand was almost certainly derived from two sources, that in the geosyncline from Appalachia and that to the west of the Catskills from the Adirondacks and the Canadian Shield. In spite of this extensive distribution, it is commonly only a few feet thick, rising locally to a maximum of 200 or 300 feet in eastern Pennsylvania. For several reasons this rather coarse sandstone can not be attributed to uplift of any consequence. In the first place, it is thin and is succeeded immediately by a more widespread

CHARLES SCHUCHERT.

Fig. 127. Middle Devonian (Onondaga) limestone resting disconformably on Upper Silurian (Cobleskill) limestone in the Bennett quarries at North Buffalo, New York. The Bertie waterlime is the source of many of the Silurian eurypterids.

and generally rather pure limestone; and, in the second place, the weathering of crystalline rocks produces vastly more mud than sand, yet this formation has practically no known shaly equivalent. It probably represents a sandy mantle that had formed over the crystalline lowlands of old Appalachia and the Adirondacks during late Silurian and early Devonian time, and was now shifted into the sea because of some climatic change that gave the streams more carrying power. It certainly does not imply the degradation of highlands.

In the fold belt of the modern Appalachians, the Oriskany formation is the chief source of pure quartz for the manufacture of glass.

The Middle Devonian begins with the *Onondaga limestone* that extends as an unbroken sheet from the Hudson Valley to central Ohio (Fig. 127). Across New York it is commonly about 100 feet thick, but it thins to the southwest. It locally grades into shale in Pennsylvania, Maryland, and Virginia, but elsewhere is generally a crystalline limestone. Corals are abundant, and reefs are widely distributed and, in places, are of large size. One of the most famous of these reefs is crossed by the Ohio River at Louisville, Kentucky, where it forms the "Falls of the Ohio." Obviously, Appalachia was

still low, so that detrital sediment was limited to a narrow belt near shore while the Onondaga limestone was forming.

The *Hamilton group*, which succeeds the Onondagan, is a great wedge of detrital material some 2500 feet thick in eastern New York and about 2000 feet thick in central Pennsylvania, thinning progressively toward the west.[4] This profound change from the calcareous deposits of Onondagan time was due, of course, to the beginning of the Acadian disturbance. Uplift in Appalachia had suddenly begun the rejuvenation of the streams and started them carrying mud and sand. This material was sorted and size-graded by the waves and currents that spread it across the shallow sea floor, and the sand and gravel were deposited in the east, while only fine mud reached beyond the geosyncline into Ohio.

Along the face of the Catskills (and down the strike in Pennsylvania) the lower part of the Hamilton group consists of dark-gray silty shale bearing marine fossils. This is succeeded by siltstone and gray sandstone, also carrying marine fossils, and these, in turn, by a redbed complex in which red shales alternate with gray sandstone and conglomerate. In this upper part, no marine fossils have been found; but land plants are preserved, the imprints of roots are common, and stumps of trees, river clams, and fresh-water fishes occur locally. In gray sandstones quarried for the dam of the Gilboa Reservoir, stumps occur in abundance at three distinct levels (Fig. 143). Fossils occur mainly in the gray sandstones, while mud cracks are widespread in the red shales.

It is quite evident that conditions had changed greatly in this locality during deposition of the Hamilton beds. At first this was a muddy sea floor, then a shallow sandy sea floor, finally a lowland across which streams threaded their way through primeval forests. These streams were choked with sand and gravel, now preserved as the gray cross-bedded sandstone and conglomerate. During floods, red mud from the warm humid slopes of Appalachia was spread widely over the interstream areas. Rainfall was seasonal, so that such deposits of fresh mud were dried and cracked into sun-baked polygons before the next flood season. Since conglomerates increase in coarseness toward the top of the group, it is evident that Appalachia was rising during Hamilton time.

As these redbeds are traced westward along the strike (Fig. 126), they are found to grade laterally into gray sandstones bearing marine fossils, and, miles farther west, the sandstones grade into siltstones

and finally into soft calcareous shales, rich in fossils of many kinds. Still farther west the shales become black. The shoreline of any particular time obviously lay where the plant-bearing redbeds are replaced by gray marine sandstone, and the redbeds here record the exposed surface of a great delta.

The Upper Devonian formations generally resemble the Hamilton group. Although divided into six stages, each of these grades laterally from redbeds in the east to black shale in the west.[5] The redbed facies is limited to the eastern margin of the Hamilton group, but in successively higher zones in the Upper Devonian it spreads farther west; obviously the exposed (subaerial) part of the delta was growing, and the shoreline was being crowded back. Late in the period the shore was far out in western New York and in northwestern Pennsylvania. This complex of marine and nonmarine strata was not the work of one great river but a compound delta formed by many streams flow-

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Fig. 128. Upper Devonian shales and flaggy sandstones of the Naples stage in the gorge of Genesee River near Mount Morris, New York.

PRESTON E. CLOUD.

Fig. 129. A small coral reef (lighter and nonbedded) in the Alpena limestone at Alpena, Michigan. Larger reefs in the same formation exceed 50 feet in thickness.

ing northwestward out of Appalachia. The subaerial part formed a wide coastal lowland some 200 miles across, and the subaqueous portion extended clear across the geosyncline. The evenly bedded siltstones and fine sandstones laid down far from shore are well exposed in the gorge of the Genesee River south of Rochester (Fig. 128).

The thickest part of the delta was in Pennsylvania, not far from Harrisburg, where the valley of the Susquehanna exposes about 13,000 feet of Middle and Upper Devonian strata, of which the upper 5000 feet are red. From central Pennsylvania the system thins to the south and west.

West of the geosyncline, in Ohio, Indiana, and Kentucky, the Devonian is thin, and only parts of the period are represented; the Middle Devonian is chiefly limestone, but the Upper is generally black shale.

Michigan Basin. Michigan was the site of a basin-like depression separated from the geosyncline by a northward extension of the Cincinnati arch, which was emergent from time to time or at least served as a threshold to prevent the spread of detrital sediments from Appalachia. Here the Middle Devonian is exceptionally well developed, mostly in a limestone facies. Coral reefs are strikingly displayed

in some of these beds (Fig. 129). Because of the difference in facies and the partial isolation, the faunas of New York and Michigan are largely different, but a few key horizons can be identified in both and permit the correlation shown in Fig. 130.

Cordilleran Province. The Devonian formations of the West are largely calcareous and generally much thinner than those of the East. They are also less well known. In the deeper part of the Cordilleran geosyncline in eastern Nevada (Eureka district) there is a thickness

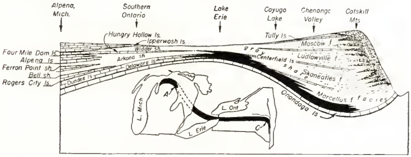

FIG. 130. Stratigraphic diagram of the Middle Devonian formations from the Catskill Mountains in New York to the Michigan Basin. The inset map shows the outcrop belt which the section follows.

Black shale is shown as solid black; gray marine shales are unshaded; the sandy marine facies is stippled; and the redbed facies is more darkly shaded. Adapted from G. A. Cooper *et al.*[3]

of 4000 to 6000 feet of limestones and calcareous shales that apparently represent nearly all of Middle and Late Devonian time. Elsewhere, in general, only parts of the Middle and Late Devonian are represented, and, except in the Canadian Rockies (Fig. 131) and in the lower Mackenzie Valley, the formations are but a few tens to a few hundreds of feet thick. Nevertheless certain horizons are represented by very distinctive and widely distributed faunas.

Perhaps the most interesting of these is the *Stringocephalus fauna* of Middle Devonian time, marked by the presence of the large and striking brachiopod from which it is named (Fig. 132). The original home of this brachiopod is Eurasia. It was first discovered in America in the limestones that form the "ramparts" of the Mackenzie River east of Alaska and has since been found in Manitoba, Utah, and Nevada.

Another widespread horizon is the *Theodosia hungerfordi zone* in the Late Devonian, which is best known in Iowa but is also widely

spread in the Cordilleran region from Arizona north into Canada and west to the Pacific coast (California).

In the lower part of the Mackenzie Valley the Middle and Upper Devonian formations thicken greatly to the north and pass largely into detrital sediments, indicating local highlands in the far north. In Ellesmere Land, west of northern Greenland, there is also a very thick Devonian section of coarse detritus.

Special interest attaches to the nonmarine strata of East Greenland, which contain a marvelous record of the earliest known land vertebrates along with abundant fishes and land plants.[6] These deposits include red and gray sandstones and shales and at the base have thick, coarse conglomerates. The whole series, which reaches a thickness of at least 3000 and possibly 10,000 feet, implies the rather rapid erosion of near-by *highlands that lay to the east of the present coast* of Greenland.

CHARLES D. WALCOTT.

Fig. 131. Mount Devon, about 20 miles north of Lake Louise in the Canadian Rockies of Alberta, exposing about 2000 feet of Devonian limestones.

The "Old Red Sandstone" of Europe

The early Paleozoic systems (Cambrian to Silurian) have yielded abundant remains of marine life, but not until the Devonian do we get the first clear glimpse of the creatures of the land and the streams. There is special fascination, therefore, in the nonmarine Devonian rocks which hold the record of the primeval spread of the forests and the coming of air-breathing land vertebrates. The American formations of the Catskill delta have been noted; in the British Isles similar deposits, long known as the "Old Red Sandstone," are vastly thicker and more fossiliferous. They lie in a series of five structural basins (Fig. 133) that were formed between the ranges of the old Caledonian mountains. During Devonian time these basins received the sediments from the rugged mountains just as the California Trough is now being aggraded by the streams from the Sierra Nevada. The several narrow basins subsided as they were filled, so that vast thicknesses (up to 37,000 feet) of sands and muds accumulated without allowing the surface of the basins to sink below sealevel.

Fig. 132. *Stringocephalus*, a large brachiopod characterizing a widespread Devonian horizon in western America and in Eurasia. Natural size.

The conditions of deposition and the nature of the climate may be inferred from the study of these rocks and their fossils. The sediments were commonly poorly sorted and they vary greatly from place to place, these features suggesting the work of streams rather than the sea. Conglomerates locally of great thickness and in places including coarse blocks several feet in diameter represent fans built where torrential streams debouched into the basins. The purer sandstones are commonly cross-bedded, like the channel sands of streams. The siltstones and shales are marked with mud cracks at many horizons, and

in places bear the imprints of Devonian raindrops. Obviously these beds are the deposits of floodplains where the mud spread during the wet season lay exposed during the dry months that followed.

Although red is the dominant color, there are also thick members of greenish-gray sandstone and siltstone and gray shales. The red sediments are completely oxidized; hence they must have come to rest where the drainage permitted good aeration of the soil during the dry seasons. The gray beds, on the contrary, were formed where the ground water stood near the surface, or at times when rainfall was distributed throughout the year so as to prevent deep drying and oxidation. The widely distributed mud cracks bear witness to seasons of drought, but there are no bedded salt or gypsum deposits in the series, and dune sands are lacking or unimportant. Moreover, the abundant fossils show that this was not a desert. Instead, it must have been a region of semiarid climate, one in which the rainfall was largely seasonal, so that periods of plentiful moisture alternated with seasons of drought. This would cause the frequent wetting and drying of the soil so conducive to the formation of red sediments and would account for the mud cracks on the wide floodplains.

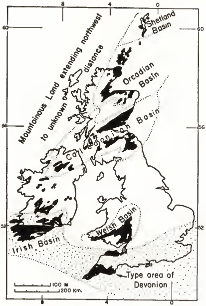

Fig. 133. Map showing the distribution of the Devonian formations (*black*) in the British Isles. The stippled area represents the probable extent of marine and brackish water in Devonian time. The other areas, outlined by dotted lines, were intermont basins. After Barrell.

The dominant animals of the Old Red are fresh-water fishes, of which there are many kinds. Eurypterids also are common in the lowest beds. Although the earlier eurypterids are generally associated with marine fossils, those of the Devonian and later times are always found with fresh-water fossils and land plants, indicating that by Devonian time they had invaded the rivers, either to spawn or to make their permanent abode. Plant fossils are locally abundant.

Devonian Disturbances in Other Countries

During early Devonian time the northern part of the British Isles was the theatre of igneous activity on a large scale. To this time also belong the volcanic rocks in the midland belt of Scotland, as well as part of the granites of this region and of the English lake district. In western Germany the Lower Devonian alone has a thickness of 9750 feet and is evidence that high mountains existed here also.

The most extensive orogeny was in eastern Australia, where the Kanimbla Mountains were formed at the close of the period in a fold belt that stretched the full length of the eastern border of the continent. Much igneous activity had occurred during the period in this region, and the Devonian strata and associated volcanics are said to be over 30,000 feet thick. The uplift and folding at the close of the Devonian were accompanied by the intrusion of granite batholiths.

Eria, a Great Northern Land Bridge

Throughout Devonian time North America was apparently connected with Europe by a land bridge which later subsided beneath the north Atlantic. This hypothetical land has been called *Eria*. Although the evidence for such a land bridge is circumstantial, it is none the less convincing.

The Acadian folds cross Nova Scotia and Newfoundland and strike along a great circle directly toward Ireland. The present ragged coast lines of Acadia and Newfoundland show that these mountain folds have been broken off and must originally have extended farther east. Likewise, the Caledonian ranges formed in western Europe at the close of the Silurian follow the axis of Scandinavia but curve westward across Scotland and Ireland to strike directly toward the Acadian area. These folds have also been broken off at the west. During Devonian time, moreover, the "Old Red" sediments, which reach such a vast thickness, were coming chiefly from the northwest into Ireland and Scotland from highlands that have since become submerged in the Atlantic. In short, there is clear structural evidence of land extending northeast from the Acadian area and southwest from Britain, and the folds, although of different age on opposite sides of the present ocean, are almost precisely in line. Conclusive evidence that these two lands met is to be found in the land plants and fresh-water animals preserved in the Devonian rocks of the two regions, which are so

much alike on both sides of the Atlantic that it seems clear they were free to migrate across an easy land bridge. How wide the bridge may have been is now impossible to determine, but it seems probable that the shallow bank between Britain and Greenland, from which the island of Iceland rises, may be a vestige of this old land.

Climates of Devonian Time

The temperature was doubtless diversified over the Earth and varied locally with changes in relief and in air and ocean currents, but the most striking evidence we have indicates mild climate and a lack of strongly marked climatic belts. For example, coral reefs were more extensively developed in the Mid-Devonian seas than at any other time save the Mid-Silurian. Furthermore, the same genera and species existed in Kentucky, Ohio, New York, and the Hudson Bay region. The same disregard for climatic zones is seen in the fact that several faunas migrated from Eurasia into America by way of the lower Mackenzie basin. This route brought them well within the Arctic Circle and through present polar seas. Examples of this kind are (1) the *Stringocephalus* and (2) the *Hypothyridina faunas* of the Middle Devonian, and (3) the *Theodosia hungerfordi fauna* of the Upper Devonian.

Furthermore, the land plants are much alike in the British Isles, Spitzbergen, East Greenland, and New York. Such distribution of animals and plants would have been impossible if the climatic zones had been strongly marked as they are now.*

The redbeds of the Catskill region and East Greenland, like the Old Red of Europe, have been interpreted by some geologists as the deposits of arid basins, but the abundance of fossils, the general lack of wind-blown sands, and other features make this altogether improbable. In the modern world, red soil and red mantle form chiefly where the climate is humid and warm, and where the rainfall is seasonal. The warmth and humidity provide ideal conditions for the thorough oxidation of the mantle, so that the iron is changed to a reddish hydroxide. Strong seasonal rainfall in the basins of deposition allows

* The few supposed cases of glacial evidence appear to mark local glaciers, probably of the valley glacier type (Kirk, 1918, in Alaska). The best evidence occurs in South Africa, where the late Lower Devonian (Table Mountain series) has much to indicate the presence of glaciers moving from west to east. On the other hand, Ruedemann has shown that Clarke's evidence of shore ice in New York and Quebec is groundless.

drying and decay of the vegetation, which would otherwise tend to reduce the iron and produce dark colors. It also favors the formation and preservation of mud cracks, a very striking feature of the redbeds. It appears probable, therefore, that the Devonian red sediments were derived from the warm and humid slopes of the rising mountains under a marked seasonal rainfall, and that the basins of accumulation were less humid than the upland slopes.

Devonian Life

Evolution among the Marine Invertebrates. The Devonian seas swarmed with animals of many kinds (Figs. 134, 135). Where the seas were clear, *corals* (Pl. 7, figs. 1–3) made reefs, and some of the species reached large sizes. The greatest of all cup corals, *Siphonophrentis gigantea,* produced individual coralla as much as 3 inches across and 2 feet high. Compound species locally formed "heads" as

BUFFALO MUSEUM OF SCIENCE.

Fig. 134. Reconstruction of a bit of a Devonian coral reef, with associated seaweeds, sponges, and other marine animals: a, crinoid; b, seaweed; c, corals; d, sponges; e, a snail. About $\frac{1}{10}$ natural size.

great as 8 feet across. Among these reefs the honeycomb corals were especially prominent. *Bryozoa* of many kinds, and crinoids as well, also lived on the reefs, and the hydroid "coral," *Stromatopora*, formed encrusting deposits, cementing other shells together.

Brachiopods (Pl. 7, figs. 6–16) were now at their climax, and the spirifers were particularly varied. No fewer than 700 kinds of Devonian brachiopods are known in North America alone. *Pelecypods* (Pl. 8, figs. 1–6) found the muddy and sandy bottoms of the Middle and Late Devonian seas to their liking and now became more common and more diversified than ever before. Some of these, adapted to burrowing, took on forms much like the modern razor clams, whereas others were attached by elastic threads like modern pearl clams and, like them, became "winged." The *gastropods* (Pl. 8, figs. 13–15) are not as a rule well preserved or highly diversified. *Cephalopods* were varied, although only locally abundant. In some of them the margins of the septa were folded or ruffled so that the sutures between septa and shell show strong flexures (Pl. 8, figs. 9 and 12). These are the primi-

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Fig. 135. Life of a Devonian sea floor. Center, a frilled cephalopod (Gyroceras) attacking a trilobite (Homalonotus); left, a large crinoid (Scyphocrinus) and below it a spiny trilobite (Terataspis); right, other trilobites, shells, and seaweeds.

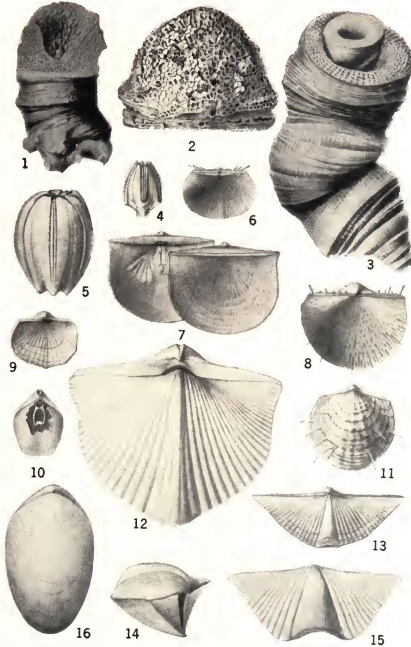


Plate 7. Devonian Corals (1–3), Blastoids (4–5), and Brachiopods (6–16).

Fig. 1, *Cystiphyllum vesiculosum;* 2, *Favosites conicus;* 3, *Heliophyllum halli;* 4, *Pentremitidea filosa;* 5, *Nucleocrinus verneuili;* 6, *Chonetes coronatus;* 7, *Stropheodonta demissa* (dorsal view of shell and interior of pedicle valve); 8, *Productella callawayensis;* 9, *Tropidoleptus carinatus;* 10, *Cranæna sullivanti;* 11, *Atrypa rockfordensis;* 12, *Costispirifer arenosus;* 13, *Mucrospirifer mucronatus;* 14, 15, *Platyrachella mesistrialis* (oblique view with ventral beak down, and dorsal view); 16, *Rensselæria elongata.* All natural size. Drawn by L. S. Douglass.

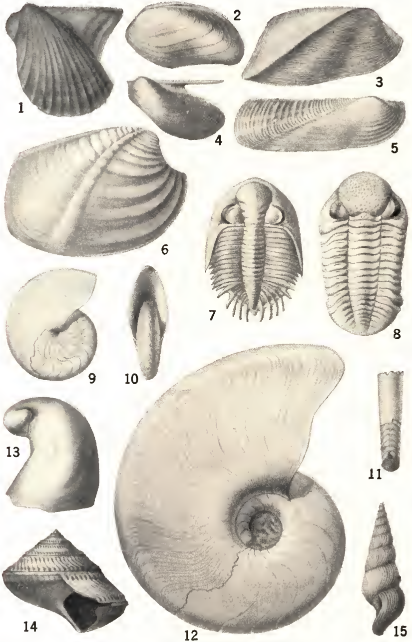


Plate 8. Devonian Pelecypods (1–6), Trilobites (7–8), Cephalopods (9–12), and Gastropods (13–15).

Fig. 1, *Cornellites flabellus;* 2, *Nyassa arguta;* 3, *Goniophora hamiltonensis;* 4, *Leptodesma longispinum;* 5, *Orthonota undulata;* 6, *Grammysia bisulcata;* 7, *Greenops boothi;* 8, *Phacops rana;* 9, 10, *Tornoceras uniangulare;* 11, *Bactrites arkonensis* (fragment); 12, *Agoniatites vanuxemi;* 13, *Platyceras reflexum;* 14, *Bembexia sulcomarginata;* 15, *Loxonema hamiltoniæ* All natural size. Drawn by L. S. Douglass.

tive forms of the *ammonites,* a tribe of cephalopods that became steadily more important in the Late Paleozoic seas and dominated all other kinds of molluscs during the Mesozoic era. Their appearance at this time is one of the most significant advances in the marine life of the Devonian period.

Although trilobites (Pl. 8, figs. 7, 8) were on the decline and relatively few kinds are found, they were locally abundant, and some among them were of large size, one species of *Dalmanites* reaching a length of 29 inches, probably the record for all time.

Groups that were less common but on the increase were the *blastoids* (Pl. 7, figs. 4, 5), *starfishes,* and *echinoids.* A great slab of Ham-

American Museum of Natural History.

FIG. 136. Model of the giant arthrodire, *Dinichthys.* Actual length about 20 feet.

ilton sandstone, found at Mount Marion, New York, and now in the State Museum at Albany, originally preserved the casts of more than 400 starfish, some of which died hovering over clams they were in the act of devouring just as the modern starfish eat oysters. *Crinoids* were as common and varied as in the Silurian. Siliceous sponges, somewhat like the modern "Venus' flower basket," were locally abundant, especially in the Late Devonian in central New York.

Ascendancy of the Fishes. Although scattered bony plates occur in rocks as old as Middle Ordovician, fish remains are extremely rare until we come to the Devonian, and then they are locally abundant and highly diversified. This must have been a time of rapid evolution for the group, since before the close of the period several of the great orders of fishes were present, and they were widely distributed in the seas and in lakes and streams.

Sharks were common in the seas, but are known chiefly from teeth and fin-spines, since their skeleton is cartilaginous and their scales microscopic. The majority of the sharks were small and of normal form, but one group specialized remarkably and developed into the

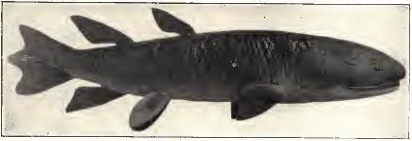
Fig. 137. The African lungfish, Protopterus. Left, the fish in its "cocoon" as it was shipped from Africa to Chicago in an open tin can. The shipment was in transit for more than 6 months, during which time the fish lived thus encased in dried mud. Right, the same after being placed in an aquarium. From Turtox News, through the courtesy of the General Biological Supply House, Inc.

largest animals of the time. These are the *Arthrodira*, of which the genus *Dinichthys* (Fig. 136) reached a length of 20 feet. Unlike other fish, the arthrodires bore a heavy armor of bony plates that not only covered the head but also, like a cuirass, reached back over the front part of the body. The plates that covered the jaws were developed into shears that took the place of true teeth. The arthrodires were an aberrant group of sharks that evolved rapidly, achieved great size, became too specialized, and died out early in the next period.

Far greater interest attaches to the *Choanichthyes*, a primitive stock of air-breathing fishes that was dominant in Devonian time but is now nearing extinction. The name refers to a feature not found in any other fishes, namely, a pair of openings in the roof of the mouth which communicate with the external nostrils and permit breathing through the nose, as in land animals (Gr. *choana*, internal nostril, + *ichthyos*, fish). This is the stock from which all the higher vertebrates were to develop.[7]

At least five genera of this group are still extant, but unfortunately they occupy remote parts of the world and are not commonly known. Perhaps the most remarkable is *Protopterus*, the African lungfish (Fig. 137), which lives in the upper reaches of the Nile, where humid winter seasons alternate with dry summers. During the wet season *Protopterus* swims about and breathes by means of gills like any other

fish; but during the summer, when the swamps go dry, it burrows down into the mud and makes a juglike chamber, where it goes into a rest-



Yale Peabody Museum.

Fig. 138. The Devonian crossopterygian, *Eusthenopteron foordi*, from the Upper Devonian beds near Escuminac, Quebec. Actual length of the fish about 2 feet. A model by George G. Simpson.

ing stage like hibernation. Unlike the condition in most fishes, its swim-bladder is connected with the throat, so that air can be inhaled or exhaled at will; furthermore, this organ is supplied with a plexus

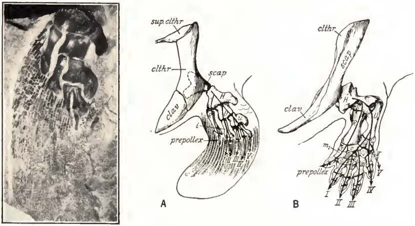


Fig. 139. Resemblances between a crossopterygian fin and the limb of a primitive land animal. Left, unretouched photograph of the left front fin of *Eusthenopteron foordi;* center, diagram of the skeletal elements of the same fin; right, the corresponding limb of a late Paleozoic amphibian, *Eryops*. Photograph from W. L. Bryant; diagrams after W. K. Gregory. For a restoration of *Eryops*, see Fig. 193.

of blood vessels which have the power to absorb oxygen and discharge carbon dioxide. In short, the swim-bladder in this fish is a rudimentary lung in both structure and function. As the water disappears

during the dry season, *Protopterus* is thus able to breathe air like a land animal; but with the return of the wet season it wriggles out of its mud "cocoon" and swims and breathes again like a normal fish.

A different and perhaps more significant habit is shown by another living lungfish, *Neoceratodus*, which is found in the rivers of arid northern Australia. During the dry seasons it continues to swim about, merely coming to the surface more often for a breath of air, as the water becomes so stagnant that gill-breathing is inadequate. Its rudimentary lung merely supplements the gills at all times, but it permits this fish to live where the water becomes so stagnant and foul that others perish.

In Devonian time the Choanichthyes included two great tribes, the *Dipnoi* and the *Crossopterygii*. The living examples described above belong to the Dipnoi, and like all the fossil representatives of that group, they are deficient in having very weak fins, in lacking true teeth, and in other respects which indicate that none of them could be ancestors of the higher animals. The Crossopterygii, on the other hand, show a combination of characters that makes them almost a perfect connecting link between fishes and the lower tetrapods, that is, the four-legged, air-breathing vertebrates.

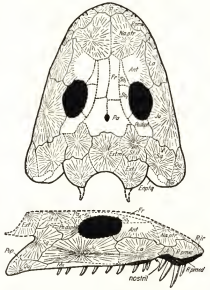


FIG. 140. *Ichthyostegia eiglei*, a late Devonian labyrinthodont from Mount Celsius, East Greenland. Dorsal and side views after Säve-Söderbergh through the courtesy of Lauge Koch. Length of skull about 6 inches.

The *Crossopterygii* (Gr. *crossoi*, a fringe, + *pterygion*, a fin) are so named because their fins have a stout muscular basal lobe beyond which the fin rays extend as a fringe. The fleshy basal lobe, lacking in other fish, is the significant thing, for it is the forerunner of the limb of higher animals.

Of Devonian Crossopterygii perhaps the best known, and certainly one of the most significant, is *Eusthenopteron* (Fig. 138), remains of which are abundant and exceptionally preserved in Upper Devonian beds near Escuminac, Quebec. Three features are noteworthy: (1)

the stout skeleton in the basal lobe of each fin (Fig. 139), (2) the pattern of bony armor plate on the head, and (3) the sharp conical teeth, in which the covering enamel is deeply and intricately infolded.

Yale Peabody Museum.

FIG. 141. A labyrinthodont tooth, side view and cross-section (×5). The creases on the surface are due to infolding of the enamel as revealed in the cross-section. Position of the section is indicated by the dashed line across the side of the tooth.

Emergence of the Tetrapods. It is no accident that the appearance of primitive tetrapods followed closely upon this rapid evolution of air-breathing fishes. In 1928 a Danish expedition working in East Greenland, under the leadership of Lauge Koch, came upon well-preserved skulls and incomplete skeletons of the oldest and most primitive of the land vertebrates yet known (Fig. 140). They occur in some abundance in nonmarine beds of late Devonian age that closely resemble the Old Red sandstone of England. The skulls range in length from 4½ to 7 inches and indicate sprawling animals shaped like a young crocodile and 3 or 4 feet long. They represent the *Labyrinthodontia*, a primitive group of amphibians, so named because the enamel on their teeth is complexly infolded, presenting, in cross-section, a labyrinthine pattern (Fig. 141). Nearly all the Paleozoic amphibia were labyrinthodonts (Gr. *labyrinthos*, labyrinth, + *odous*, tooth).

It is now quite clear how the tetrapods evolved from the air-breathing fish and why the first ones were *Amphibia*. Members of that great class, which includes salamanders, toads, and frogs, are still incompletely adapted for life on land. They return to the water to spawn and lay small and simple eggs which, like those of fishes, hatch into tadpoles that breathe by means of gills and are essentially fish-like until partly grown, when legs bud out from their sides, lungs develop from their throat, and the gills are resorbed. Then they leave

the water and breathe air.. But they still are not quite fully adapted to land life; they must return to the water to spawn, and most of them remain in moist places and spend part of the time in the water. Comparative anatomy and ontogeny both indicate that they evolved from fishes, and the geologic record indicates rather clearly when and under what circumstances the change took place.

The "Old Red" type of Devonian formations accumulated over basin floors where the rainfall was seasonal. Such conditions persisted throughout much of Devonian time in eastern North America and western Europe, and here for millions of years the fish living in the streams and evanescent lakes had to endure annual seasons of drought. Again and again the shrinking waterholes brought death and destruction—but always there were some that did not go dry, and there the survivors were crowded in stagnant water, starving for oxygen. A great premium was thus placed on ability to gulp air and to use the

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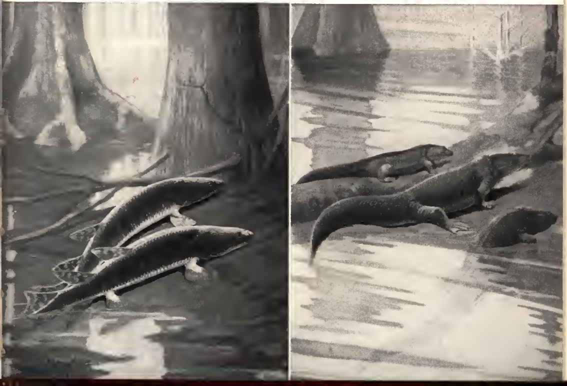
Fig. 142. Stages in the transition of the lungfishes into labyrinthodonts, as reconstructed by W. K. Gregory. Left, the Devonian crossopterygian, Eusthenopteron, leaving the water to flounder about on its strong muscular fins; right, an early labyrinthodont, Diplovertebron, from the Lower Carboniferous beds of Bohemia.



oxygen straight. Fishes with swim-bladders that could function as lungs were thus at a great advantage and were stimulated to ever greater activity as the oxygen in the water was depleted. Those with stout fins like *Eusthenopteron* could forsake their pools in the cool of the night and flounder about the banks in short forays for food. Once the lungs had reached a certain efficiency and the fins had been modified into stubby limbs, land vertebrates had arrived! The environment, of course, had not produced these modifications; it had simply selected ruthlessly those random variants that appeared from time to time and were better adapted to survive under such exacting conditions.

The transition from fish to tetrapod, as pictured by W. K. Gregory,[8] is shown in Fig. 142. It is supported by so many detailed technical facts that the Devonian crossopterygians are now accepted by virtually all zoologists as the ancestors of the tetrapods. For example, if we compare *Eusthenopteron* with an early amphibian, we find corres-

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Fig. 143. Reconstruction of the Middle Devonian forest at Gilboa, New York. Remains of this old forest were discovered during construction work for the Catskill reservoir. The foreground represents actual rock outcrops with three horizons of petrified stumps in place, and the background gives a vista into the forest as it existed in Devonian time. e, the seed-fern, Eospermatopteris; p, a primitive scale tree, Protolepidodendron.

pondence in the head armor, plate for plate; we find the same elaborately intricate infolding of the enamel of the teeth (Fig. 141); and there is a correspondence in other skeletal parts that can not be attributed to coincidence. In this connection it is significant that the Devonian labyrinthodonts are more primitive than any others yet known in at least two respects, both of which emphasize their close relationship to the fishes. One of these is the submarginal position of the external nasal openings (Fig. 140), and the other is the character of the "lateral line" system (a specialized sense organ) that has the form of subsurface canals, as in fishes, whereas in later amphibia it forms only shallow grooves.

Fig. 144. Primitive Devonian land plants. *A*, *Asteroxylon mackiei*, and *B*, *Hornea lignieri*, from the Lower Devonian beds of Rhynie, Scotland. About 1/3 natural size. After Kidston and Lang.

Land Plants and the Spread of Forests. Evidence of land plants is very scarce before Devonian time but plentiful thereafter, and by Middle Devonian time there was a considerably diversified flora of primitive trees, some of which have left petrified stumps more than 2 feet in diameter. Among these were tall, slender *scale trees* (Fig. 143), primitive evergreens with large bladelike instead of needlelike leaves, and abundant ferns and *"seed ferns."* These were the forerunners of the Coal Measures floras of Pennsylvanian time and in general were much like the latter.

Although soft-tissued plants were probably common long before the Devonian, no fossil wood has been found in pre-Devonian rocks. Yet no later age has failed to yield abundant evidence of land plants. We can not avoid the inference, therefore, that the Devonian possessed the first forests that ever clothed the lands. We need to turn to the treeless barrens of the present world to appreciate what the Early Paleozoic lands looked like and to realize the significance of this great advance in the Devonian.

The oldest known deposit of well-preserved land plants is in rocks of the Old Red series near Rhynie, in the Scottish county of Aberdeen.

The wonderfully preserved plants found there represent almost the simplest possible type of structure a land plant could have, and suggest the steps whereby an aquatic alga adapted itself for land life. Two of these earliest of land plants are shown in Fig. 144.

Associated with these plants and equally well preserved are the remains of 3 genera and 18 species of spiders, 1 form of mite, and a primitive wingless insect, showing that the air-breathing arachnids and insects had their rise at least as far back as Early Devonian time.

Primitive land plants have now been found in abundance in the Lower Devonian of Belgium [9] and of Wyoming.[10]

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CHAPTER 11

THE MISSISSIPPIAN PERIOD

The Carboniferous System. The coal-bearing rocks of Europe and eastern North America were among the first to attract the attention of geologists. As early as 1808 the Belgians referred to them as the "bituminous terraine," and in England they were long known as the "Coal Measures." The name *Carboniferous* was introduced by Conybeare and Phillips in 1822, when they attempted the first general account of the geology of England and Wales. The word "system" had not yet come into vogue, and they proposed the term "Carboniferous order" to embrace the Coal Measures and three underlying groups: (1) the Millstone grit and shale, (2) the Mountain limestone, and (3) the Old Red sandstone. The "Old Red" was transferred to the Devonian system in 1839.

The Coal Measures in time were distinguished as the *Upper Carboniferous*, and the barren groups below as the *Lower* or *Sub-Carboniferous*. The same distinction was useful in America, where the Upper Carboniferous rocks contain practically all the rich Paleozoic coals, and the Lower Carboniferous is barren. In 1891 the U. S. Geological Survey recognized these divisions as formal units and gave each a geographic name, designating the upper the *Pennsylvanian* and the lower the *Mississippian series* of the Carboniferous system. In 1906 Chamberlin and Salisbury pointed out that these units not only differ in lithology over much of the continent but also are separated by a major and very widespread hiatus; and they argued that each should be given the rank of a distinct system. This proposal has steadily gained favor and is now accepted by nearly all American geologists.[1]

The American usage has not been adopted, however, by most European geologists, who still generally recognize the Carboniferous system.*

* The U. S. Geological Survey also officially recognizes the Carboniferous system and treats the Mississippian and Pennsylvanian as subsystems, although many members of the Survey privately advocate recognizing them as systems.

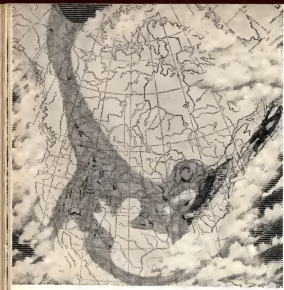


Fig. 145A (left). Early Mississippian (Middle Kinderhookian) paleogeography. Land surface lightly shaded; shallow sea deeply shaded; deep sea horizontally lined; present outcrops in black. Chiefly nonmarine deposits are marked by black lined overprint.

Fig. 145B (right). Middle Early Mississippian (Osagian) paleogeography. Symbols as above. This represents the maximum submergence for this period.

Fig. 145C (left). Middle Late Mississippian (Middle Chesterian) paleogeography. Symbols as above.

Physical History of Mississippian Time

The Mississippi Valley Seaway. The Acadian disturbance at the close of the Devonian period elevated Appalachia into mountains and transformed the surface of the geosyncline into a broad alluvial plain. The central and western part of the continent meanwhile remained low, and the next submergence brought an inland sea over the region of the modern Mississippi Valley. For the long and richly fossiliferous record formed here the Mississippian system was named.

As suggested in Fig. 145, the sea not only entered this region first but occupied it more persistently than any other during this period. Nevertheless, the water was generally shallow, and the region was partially or completely emergent at several times.

Restless Appalachia. Throughout the Mississippian period the Appalachian trough continued to subside, but, inasmuch as it was constantly aggraded by sediments derived from Appalachia, it remained for the most part an alluvial plain barely above sealevel. At times the subsidence was more rapid than the filling, and the sea crept eastward across the geosyncline only to be crowded back eventually as the heavily loaded streams from the east gained the ascendancy. Thus the shoreline fluctuated back and forth across the geosyncline while thousands of feet of detrital sediments accumulated (Fig. 148).

Meanwhile, Appalachia remained a rugged upland in spite of active erosion, and during the latter part of the period was ever more strongly uplifted until the sands derived from it spread as far west as Illinois. Obviously this ancient marginal land was rising during Mississippian time. Toward the close of the period, it was a highland, at least as far south as Alabama. At the same time movement was beginning in Llanoria, a marginal land then occupying the site of Louisiana, eastern Texas, and part of the present Gulf of Mexico. It is probable that by this movement Appalachia and Llanoria were united and the old connection to the Atlantic via Alabama and Mississippi was permanently cut off; meanwhile a new passage to the west of Llanoria and across Mexico was opened to remain a dominant seaway until the close of the era.

Beginning of Changes in the West. Early in the Mississippian period the Cordilleran trough was widely flooded, and the pattern of land and sea was similar to that of Devonian time. The presence of typical marine faunas as far north as Peace River (lat. 58°) in the Mackenzie Valley indicates that the sea for a time connected with the

Arctic. By the middle of the period, however, the sea had vanished from the northern part of the Cordilleran trough, although it persisted in the central and southern parts during much of the period, as proved by sections in southern Alberta and British Columbia, and in Utah and Nevada. Meanwhile the sea had broken across Cascadia to cover northern California, and a new trough, running near the present coastline, brought a seaway southward into central Oregon, bearing a peculiar and distinctive Eurasian fauna not known elsewhere in America. The paleogeography of this western region is still imperfectly known, and the interpretation given in Fig. 145 is tentative.

Closing Episodes of Uplift and Orogeny. In North America, Late Mississippian time was marked by more widespread disturbance than any previous part of the Paleozoic era, as mountains were made not only throughout the length of Appalachia but in Llanoria and in parts of Colorado as well. These movements were the forerunners of others that followed intermittently during the rest of the Paleozoic era and culminated in the Appalachian revolution in the Permian.[2]

Over the interior of the continent this late Mississippian unrest was marked by emergence and extensive erosion but without sharp deformation, the intense movement being confined to the marginal lands, Appalachia and Llanoria. As a result, the Mississippian strata, either in the geosyncline or through the central states, generally lie parallel to the overlying Pennsylvanian, and evidence of marginal uplift is seen only in the detrital character of the deposits.

During the long interval of erosion, the early Mississippian limestones of the Ozark region in Missouri and southeastern Kansas were subjected to erosion and developed a karst topography with many sinks and underground caverns. These were in part filled later by the basal Pennsylvanian formations.

Beginning of the Colorado Mountains. Although limestone accumulated widely over Colorado during the early part of the period, later uplift in the area of the modern Front Range caused it to be locally removed. The section restored in Fig. 146 gives the evidence for this uplift. In the rim of the Black Hills, which was far from the disturbance, Mississippian limestones are succeeded without discordance by Pennsylvanian limestones. In the Hartville uplift, however, the Mississippian limestone is overlain with spectacular unconformity by red shales and sandstones of early Pennsylvanian age, box canyons as much as 100 feet deep in the light gray limestones being filled with the redbeds.

The abrupt change from limestone to detrital sediment clearly indicates that uplift had taken place and that adjacent lands were being eroded. Indeed, the deep canyons in the Mississippian rocks prove that the Hartville region itself had been temporarily uplifted. Farther west, along the margin of the Front Range, the Pennsylvanian redbeds overlap on Pre-Cambrian granite, but their basal layers include chunks of residual chert, bearing Mississippian fossils. It is therefore evident that the Mississippian limestones were once present here and had been eroded away before Pennsylvanian time. Since the limestones are still present in considerable thickness in the Leadville

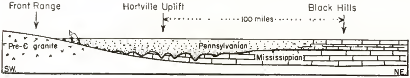


FIG. 146. Idealized section from the Rocky Mountain Front Range near Ingleside, Colorado, to the Black Hills of South Dakota, showing the relations of the Mississippian formations during Pennsylvanian deposition. Fossiliferous boulders of Mississippian rock in the basal Pennsylvanian conglomerate are indicated by the letter *b*. Length of section, about 225 miles. Vertical scale greatly exaggerated.

region farther west, the uplift was obviously between Leadville and the Hartville area, and it probably took the form of a broad arch or dome. This disturbance marks the beginning of the Colorado Mountains, an uplift that persisted into the next period.

Beginning of the Ouachita Disturbance in Llanoria.[3] A very thick mass of detrital formations in the Ouachita (*wŏsh'ĭ·tô*) Mountains of Arkansas and southeastern Oklahoma also reflects strong uplift in Llanoria near the close of the period. Llanoria was a land mass then occupying the area of the modern coastal belt of Arkansas, Louisiana, and east Texas and probably the northern part of the Gulf of Mexico. It was repeatedly uplifted during the Pennsylvanian period, and in the Permian was thrust northward, crushing the thick Paleozoic deposits of the Ouachita geosyncline and driving them northward in a great overthrust arc to form the Ouachita Mountains. The basal part of this thick detrital mass was formed, of course, during the early stages of the uplift, but unfortunately it is still not certain whether it is late Mississippian or earliest Pennsylvanian (see p. 241).

There was also marked uplift in southern Appalachia near the close of Mississippian time, producing a highland that supplied the 2000 feet of detrital sediments (Parkwood) at the top of the system and the

great volume of early Pennsylvanian sediments that are now represented in Alabama by 9000 feet of strata.

Variscan Mountains of Europe. During the Late Paleozoic, southern Europe experienced long-continued, extensive, and complicated orogeny. This resulted in a great chain of mountains (Fig. 147) that ran southeastward from Ireland across England to southeastern France, then curved northeastward across Switzerland and southern Germany into Bohemia and Austria. They have been called the Paleozoic Alps, the Hercynian Alps, or the Variscan Mountains. The last name is preferable, since these mountains had no genetic relation to the modern Alps.

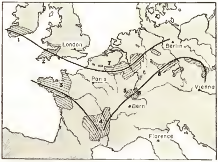


Fig. 147. Map showing distribution of the Variscan ranges of late Paleozoic date. The "stumps" of these ancient mountains are now exposed in the shaded areas. 1, southern Ireland; 2, southwestern England; 3, Armorican Massif, Brittany; 4, central massif of France; 5, Vosges Mountains; 6, Black Forest; 7, Ardennes; 8, Erzgebirge. Adapted from E. Kayser.

The growth of the Variscan Mountains involved folding and faulting as well as much igneous activity. This crustal movement embraced not a single disturbance, but three, one at the end of Mississippian time, one during the middle of the Pennsylvanian, and another at the end of the Permian. In some regions the chief disturbance came at one time, and in others at another. In parts of France and Germany the major folding occurred at the close of Mississippian time. There was also much volcanic activity during the Mississippian period in England as well as on the Continent. The Kuen-Lun Range north of the Himalayas likewise suffered marked disturbance at the close of this period.

Stratigraphy of the Mississippian Rocks [4]

Appalachian Province. The Mississippian rocks formed east of the Cincinnati arch contrast in almost every respect with those farther west. While the Appalachian geosyncline was trapping the sands and muds from Appalachia, the low Cincinnati arch served as a threshold to check the westward movement of detrital sediment. As a result the Mississippian formations of the Appalachian region are very largely sandstones and shales and, to a considerable extent, of nonmarine de-

position, whereas those formed in the Mississippi basin are mostly of limestone and wholly marine. Eastern Ohio and southern Michigan, however, are allied to the Appalachian region.

In eastern and central Pennsylvania, the Mississippian is generally divisible into two groups, *Pocono* and *Mauch Chunk*. The former, which is the older, comprises gray sandstones and siltstones with remains of land plants and thin local coal beds. Coal from this horizon near Roanoke, Virginia, was used on the frigate *Merrimac* in her battle with the *Monitor*. The Pocono has thick members of sandstone and, in the anthracite field of east-central Pennsylvania, includes rather massive beds of quartz-pebble conglomerate; it is one of the prominent ridge makers in the Appalachian folds.

In marked contrast with this, the Mauch Chunk is composed of dull red sandstones and bright red siltstones and shales attaining a total of over 3000 feet in thickness. These beds bear "fossil" mud cracks and impressions of raindrops at many horizons. Fossils are exceedingly rare and comprise only fragmentary plant remains and a variety of amphibian footprints.

Traced westward, the Pocono group interfingers with fossiliferous marine zones in western Pennsylvania and gradually passes entirely into fine-grained marine sandstones and shales (Waverly group) in Ohio. It is evident that the Pocono represents a vast delta with its highest and thickest part in eastern Pennsylvania, where it reaches a thickness in excess of 2000 feet. There the coarser sediment derived from the east came to rest on the subaerial part of the delta, while the finer material was partly carried on to form the submarine foreset slopes farther to the west and southwest. The Mauch Chunk likewise represents the subaerial deposits of a low delta plain, but it formed under conditions of marked seasonal rainfall.

A maximum thickness of more than 8000 feet is attained by the Mississippian system along the border of Virginia and West Virginia (Fig. 148). Here the middle part is largely calcareous, but the lower and upper thirds are chiefly sandstones and shales of fluvial origin representing coastal plain or delta deposits.

At the northeast end of the geosyncline there was another basin of thick deposition in New Brunswick and Nova Scotia. In this, the Acadian area, the older strata are also nonmarine. The lower part, ranging from 2800 to 3400 feet in thickness, consists of coarse and poorly sorted detrital materials such as arkose, conglomerate, muddy sandstones, and micaceous shales. These constitute the *Horton group*. In age they correspond approximately with the Pocono group farther

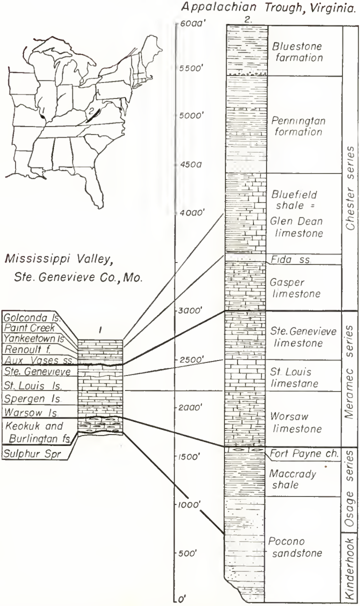


FIG. 148. Columnar sections of the Mississippian system. Left, a generalized section in the type area of the system in Ste. Genevieve County, Missouri; right, a generalized section of the Appalachian trough in Virginia. After Weller and Butts, respectively.

south. In certain layers abundant fossilized stumps of small trees stand erect where they grew.

The upper group in this region is known as the *Windsor*. It is partly marine and includes red conglomerates, red and gray shales with thin beds of richly fossiliferous dolomite, and, locally, thick deposits of gypsum. The total thickness is not less than 2000 feet. The Windsor sequence extends northeastward into Newfoundland. In age, as well as in conditions of deposition, it agrees with the Mauch Chunk.

Mississippi Valley. In the Central Interior the Mississippian strata are predominantly limestone and have a normal thickness of 2000 to 2500 feet. The section here is represented in Fig. 148.

The *Kinderhook series,* formed in the invading seas, varies greatly from place to place because of the local influence of terrigenous sediments from the submerging lands. It includes sandstones, shales, and limestones which bear many local formation names. A thin basal member of black, fissile shale (Chattanooga) is present over a very large southern area. In eastern Tennessee, Kentucky, and Ohio, that is, east of the Cincinnati arch, this black shale thickens to over 100 feet and interfingers with the gray fossiliferous shales of the lower part of the Pocono group. Gray shale or sandstone or limestone succeeds the Chattanooga shale to complete the Kinderhook series. In northeastern Ohio this facies includes the *Berea sandstone,* one of the stones most widely used for carved trim.

The succeeding *Osage series* reflects a clearing of the waters as the inundation reached its maximum. It consists mostly of limestone and is remarkable for the amount of chert, which commonly occurs in the form of nodules or lenses in the limestone but locally replaces thick beds of the latter over considerable areas. It bears the lead and zinc ores of the Joplin district of Missouri, Oklahoma, and Kansas, where it is very siliceous and is known as the *Boone chert.*

The *Meramec series* consists of purer and less cherty limestones which locally pass into oölites on a scale unequaled at any other horizon in America. The Salem limestone of Indiana, known to the building trades as *Indiana limestone,* is the most extensively quarried building stone in the United States. Being soft and uniform in texture, it tools easily and is therefore much used for copings and exterior trim as well as for marble finish in lavatories. There are probably few cities east of the Rocky Mountains that do not have some public buildings trimmed with this stone. Most of it is supplied by the

enormous quarries about Bedford (Fig. 149), which place Indiana far in the lead among the states producing finish building stone. In the last two decades the annual output from these quarries has ranged between 1,000,000 and 1,500,000 tons.

The most widespread member of the Meramec series is the *St. Louis limestone,* a purer and more compact stone which forms the conspicuous bluffs of the Mississippi River near St. Louis and stretches continuously from Iowa to Alabama as one of the greatest sheets of limestone in this country.

Indiana Limestone Company.

FIG. 149. Quarry of the Indiana Limestone Company in the Bedford oölite, near Bedford, Indiana.

The *Ste. Genevieve limestone,* next younger than the St. Louis, is likewise pure but inclined to be oölitic. It has suffered much underground solution where it floors large areas in the Ohio Valley. Mammoth Cave and thousands of others in the "Land of Ten Thousand Sink Holes" in Kentucky are excavated in this formation.

The *Chester series* is formed of alternating sandstones, shales, and limestones that have a combined thickness of 1000 to 1500 feet and

are grouped into more than a dozen formations in western Kentucky and Illinois. The spread of much sand and mud over the Mississippi basin at this time reflects, of course, uplift in southern Appalachia and Llanoria.

In the Ouachita trough, particularly, the latest Mississippian and early Pennsylvanian formations are very thick and almost wholly detrital. These sediments are thickest and coarsest in their southern exposures, where they form the Ouachita Mountains of Arkansas. This makes it clear that they were derived from Llanoria. Unfortunately there is still some uncertainty as to what portion of this vast wedge of detrital sediments belongs in the Mississippian system. In the Ouachita Mountains of Arkansas more than 2 miles of nearly unfossiliferous beds (Stanley shale overlain by Jackfork sandstone) lie between the Devonian and a very early Pennsylvanian horizon. These formations are made of dark detrital sediments with no limestones and little evidence of marine deposition. The sands in both are irregularly bedded and much rippled. Fragments of land plants are abundant but generally macerated. The sediments were obviously deposited over a low delta plain in front of a rising land mass. In the basal part of the Stanley formation there are three to five beds of tuff, ranging in thickness from 6 to 85 feet, indicating that the rising land bore active volcanoes.

The fossil evidence of the age of the Stanley and Jackfork formations is inadequate. The very few marine fossils found are badly preserved and not very significant for exact dating. The more abundant land plants are generally too much macerated to permit exact identification. As the whole mass was later thrust northward upon rocks of a different province, it is now impossible to trace the Stanley and Jackfork into fossiliferous equivalents. Present opinion favors a very early Pennsylvanian age for these deposits. If this is true, then the marked uplift in Llanoria was delayed until the very close of the Mississippian period.

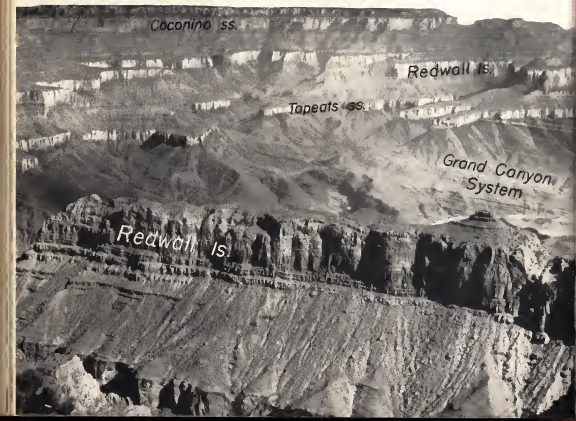
Cordilleran Region. Throughout the Rocky Mountain region the Mississippian system is represented by limestone, commonly massive and cliff-forming. Although it bears local names in different areas, it must originally have been a vast sheet of limestone strata stretching continuously from Nevada to the Black Hills, Yellowstone Park, and the Canadian Rockies. It is the cliff-forming *Redwall limestone* of the Grand Canyon (Fig. 150), and the *Madison limestone* of the northern Rockies. It reaches a thickness of 1200 feet in the vicinity

of Yellowstone National Park and continues far north into Canada. This limestone is all of Early Mississippian age (Kinderhook-Osage).

The upper part of the Mississippian system is less well developed and less well known, but in parts of Utah, Nevada, and Idaho, and locally farther west, it is represented by thick masses of limestone. In the Oquirrh Range south of Great Salt Lake, for example, the Mississippian formations, mostly calcareous, are approximately 6000 feet thick, and of this nearly 4000 feet is believed to be of Chesterian age. Local formation names are used throughout the West, and a satisfactory synthesis is not yet possible.

CARL O. DUNBAR.

Fig. 150. North wall of the Grand Canyon opposite Sunrise Point, showing the Redwall limestone cliffs midway between the basal Cambrian (Tapeats) sandstone and the Mid-Permian (Coconino-Kaibab) formations that rim the canyon. The cliff in the immediate foreground is a spur of the south wall. Pre-Cambrian Grand Canyon system may be seen dipping to the right below the Cambrian.



Climate

The marine life gives no striking evidence of the climate of Mississippian time. The extraordinary abundance and variety of the crinoids in some of the formations, and the very extensive limestones, suggest temperate or warm water. It is a matter of surprise that reef corals were not common again as they were in the Middle Devonian, especially since Mississippian corals of reef-making types are known on the arctic coast of Alaska. However, since corals were never again prominent in the Paleozoic, it seems probable that their decline was due to factors other than climate.

The humidity over the lands certainly differed from region to region, and it likewise changed greatly in some regions during the period. For example, the nonmarine and brackish-water deposits of the Pocono sandstone contain so much organic matter that they are commonly gray or dark in color, and in places in Pennsylvania and West Virginia include thin beds of coal. These features clearly indicate swamps on a rather humid delta plain. In the same general region, however, the overlying Mauch Chunk redbeds have been thoroughly oxidized and with their abundant mud cracks and rain imprints bear evidence of extended droughts, suggesting a climate of marked seasonal rainfall. Evidence of considerable aridity is seen in Nova Scotia and Newfoundland, where the Windsor redbeds include extensive gypsum deposits and locally even salt, both of these being precipitates from the water of partially land-locked lagoons. In Michigan also there are red shales rich in brines which are the principal source of the salt manufactured in the Saginaw Valley.

In eastern Australia there is evidence of glacial conditions, as shown by the Kuttung series of volcanics and nonmarine, detrital sediments that are associated with varve clays and followed by tillites (Seaham).[5] The Australian geologists believe that this glaciation took place at some time during the Late Carboniferous (Pennsylvanian) period, but, since the Kuttung beds include fossil plants (Rhacopteris flora) that characterize the Lower Carboniferous in other continents, Schuchert thinks it more probable that the glaciation took place toward the close of the Lower Carboniferous.[6]

Life of Mississippian Time

Marine Invertebrates. Marine animals are still much better known than the land life of this period, for the continental sediments accu-

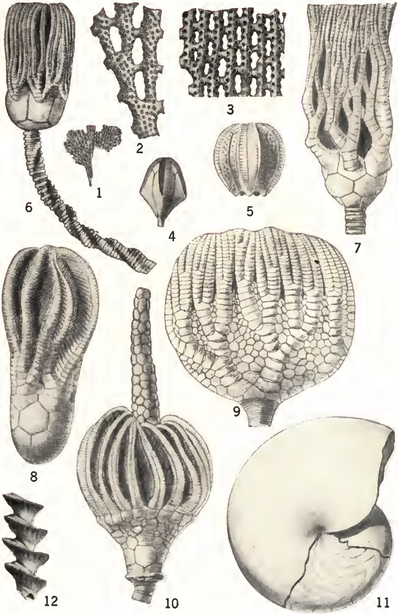


Plate 9. Mississippian Bryozoa (1–3, 12), Blastoids (4, 5), Crinoids (6–10), and Ammonite (11).

Figs. 1, 2, *Polypora cestriensis* (×⅔ and ×6); 3, *Fenestella cingulata* (×6); 12, *Archimedes wortheni*, the screw-like axis of a colony; 4, *Pentremites pyriformis;* 5, *Cryptoblastus pisum;* 6, *Platycrinites hemisphericus;* 7, *Cyathocrinus multibrachiatus;* 8, *Agassizocrinus dactyliformis;* 9, *Forbesiocrinus wortheni;* 10, *Batocrinus pyriformis;* 11, *Imitoceras rotatorius.* All natural size except Figs. 1–3. Drawn by R. G. Creadick.

mulated under conditions poorly suited to the preservation of fossils, whereas the shallow, limy sea floors harbored life of the greatest luxuriance.

Although clearly evolved from Devonian life, the Mississippian faunas were given a distinctive character by the decline of such groups as the corals and trilobites and the great expansion of others like the echinoderms, the lacy bryozoa, and the spiny brachiopods.

FIG. 151. The melon echinoid, *Melonechinus*. Part of a slab of limestone near St. Louis, with several specimens partly embedded in the matrix. These echinoids are about the size of a small cantaloupe, which they resemble in shape.

Echinoderms flourished as never before. *Crinoids* (Pl. 9, figs. 6–10) grew in such luxuriance that their dismembered plates contributed largely to the making of thick crinoidal limestones, some of which have a large areal extent. No other geologic system has yielded such a variety or such numbers of well-preserved specimens of this class. *Blastoids* (Pl. 9, figs. 4, 5) were also at a climax, the typical bud-shaped species (genus *Pentremites*) being particularly characteristic of this time. Starfishes appear to have been rare, but sea-urchins of a few kinds were locally abundant. The most striking of these were large melon-shaped echinoids (*Melonechinus,* Fig. 151) found chiefly in the St. Louis limestone.

The *Foraminifera* for the first time assumed an important role as rock makers. A single type, *Endothyra,* occurs so abundantly in the

Salem (Bedford) oölite that the formation locally takes on the character of a foraminiferal limestone. This genus is comparable to the modern *Globigerina* in size, but it probably did not float, as that genus does, and probably did not form foraminiferal ooze on the deep sea floor.

Corals persisted throughout the period but generally were neither varied, reef-making, nor especially common. The most conspicuous

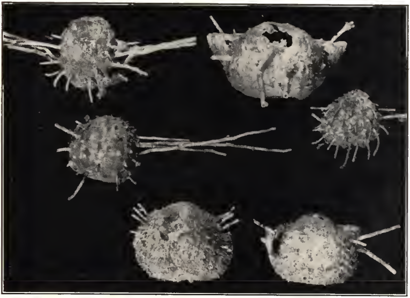


FIG. 152. Productid brachiopods. These are Permian species etched free of the stone. Similar forms were common in the Mississippian seas.

type in the interior seaways was a compound tetracoral (*Lithostrotionella*) that, during the St. Louis epoch, formed "heads" as much as 2 feet across. On the other hand, we must note the complete absence of the honeycomb coral (*Favosites*), which was so conspicuous in the Devonian reefs.

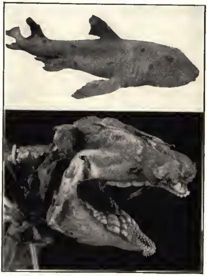
Bryozoa were again very numerous, and the lacy types (fenestellids) now reached their greatest variety. Among these the genus *Archimedes*, with its thickened and spirally twisted axis, is most distinctive (Pl. 9, fig. 12).

Brachiopods continued to be the dominant kind of "shellfish," and many of them were much like the Devonian forms, differing only in specific details, but the climactic expansion of the spiny-shelled forms

of the tribe of *Productus* (Fig. 152) gave a different aspect to the fauna as a whole. So common were these species in this and the two following periods that the inundations of the Late Paleozoic have been called the *Productus seas.*

Molluscs continued in considerable variety, and in the sandy sediments of the Pocono group small clams and gastropods are locally more common than any other fossils. The Salem oölite includes a large number of tiny snails. Perhaps the most significant molluscan advance is among the *goniatites* (Pl. 9, fig. 11); these primitive ammonites were much more common in Europe, however, than in America.

Trilobites had already declined almost to extinction, and the remaining species were small and rather rare. No trace of insects has yet been found, though the high development of that group in the next system suggests strongly that they were actually present in Mississippian time.



Yale Peabody Museum.

FIG. 153. Modern shell-crushing sharks. Above, the living bull-head shark, *Gyropleurodus francisci*, from the Gulf of California; below, skull of the closely similar Port Jackson shark of Australia, showing the jaws paved with blunt teeth which serve to crush the shells of molluscs. These fish range from two to three feet in length.

Vertebrates. *Fishes* were locally abundant, though less varied apparently than they had been in the Devonian. The best-known group is the shell-crushing sharks, whose blunt, "pavement" teeth and fin spines alone are preserved (Fig. 153). This apparently was their heyday, for nearly 300 species are known from the Mississippian rocks but only 39 from the preceding and 55 from the following system. Since their modern descendant, the living Port Jackson shark, feeds upon crustaceans and certain shellfish, it is not improbable that the rise of the shell-crushing sharks in the Devonian and their success in the Mississippian contributed to the decline of the trilobites.

Land animals left an indisputable record in the form of numerous footprints, and in 1941 actual skeletal remains were found in the Mauch Chunk beds in West Virginia.[7] In Europe, also, the skeletons

of small, salamander-like amphibia have been found. The footprints are most common in the redbeds of the Mauch Chunk, where they are associated with mud cracks and rain imprints. Doubtless many of these record the tragic search for water as the vanishing mudholes gave way to barren flats during the summer droughts. Yet among them there may be the hallmarks of destiny, for some of these restless creatures, driven by their extremity, were to develop agility and freedom from the water that would enable them in the coming ages literally to inherit the Earth.

Land Plants. Land plants were, of course, as abundant as in the Late Devonian, but their remains are lamentably broken and macerated in the deposits available to us. So far as is known, they were much like those of the Pennsylvanian, which will be described in Chapter 12.

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[2] *Late Paleozoic Crustal Movements of Europe and North America;* by R. C. Moore. Bulletin of the American Association of Petroleum Geologists, Vol. 19, 1935, pp. 1253–1305.

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Chapter 12

THE PENNSYLVANIAN PERIOD

It is fitting that this great coal-bearing system should be named for the chief coal-producing state in America and the one where it was first comprehensively studied. Here also the coal floras are found in greatest variety, though the best marine sequence occurs in midwestern states from Nebraska and Kansas to Texas.

Physical History of North America

Coal Swamps of the Eastern Interior

At the beginning of this period the central interior of the United States was a vast lowland hemmed in on the south and east by the mountainous borderland of Llanoria and Appalachia (Fig. 154). The Canadian Shield was apparently a plain of low relief stretching away to the north, while borderlands of undetermined extent and relief formed the western margin of the continent.

Early Pennsylvanian formations are restricted almost entirely to the geosynclinal areas, as indicated in Fig. 154*A*. The sea entered the Cordilleran trough from the southwest, and there the deposits are marine and mostly limestone. Another seaway reached the Ouachita trough via Mexico and Texas and pushed eastward along the north side of Llanoria. Subsidence was rapid here all the way from Texas to West Virginia, but the marginal highlands supplied mud and sand in such quantities that the trough was filled to sealevel most of the time as far west as Oklahoma. Over the subsiding lowland thus maintained, great swamps developed in which vegetation accumulated to be transformed later into the phenomenally rich coal deposits of Alabama and West Virginia.

Before the middle of the period submergence spread northward over most of the central and western states (Fig. 154*B*), and the sea reached temporarily to the foothills of Appalachia, covering, at a maximum, approximately 30 per cent of North America. Even then, however, the heavily loaded streams from the east were struggling to crowd

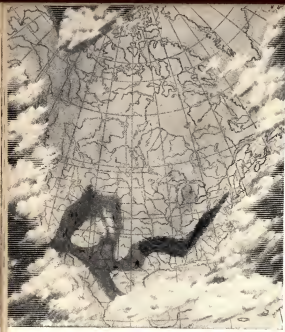


Fig. 154A (left). Early Pennsylvanian (Lampasan) paleogeography. Land surface lightly shaded. Black line shading in Appalachian trough marks dominantly nonmarine deposits.

Fig. 154B (right). Early Middle Pennsylvanian (Desmoinesian) paleogeography. Symbols as above. This represents the maximum submergence of the period.

Fig. 154C (left). Late Pennsylvanian (Early Virgilian) paleogeography. Symbols as above.

back the sea and to build out broad alluvial plains. Slight subsidence repeatedly brought the shoreline far to the east, only to retreat again as the shallow sea was filled and transformed into swampy lowland. The marginal lands were repeatedly uplifted, while the broad interior basin slowly sank until its pre-Pennsylvanian floor lay from two thousand to several thousands of feet below the surface. Meanwhile filling kept close pace with subsidence all the way from Pennsylvania to Kansas and Nebraska.

In the vast swamps thus repeatedly formed, vegetation accumulated to form coal. In part the swamps were marginal to the sea, but in part they were formed by irregular warping far from shore. Within this far-flung lowland, subsidence was most rapid along the Appalachian and Ouachita geosynclines and in the Illinois basin, and in these areas the Pennsylvanian system is several thousands of feet thick. A small basin in Rhode Island may have been completely isolated from the rest as an intermont trough. At the north end of the old Appalachian trough lay the Acadian basin, in which thick nonmarine deposits were formed that contain the important coals of Nova Scotia, Cape Breton, and New Brunswick. This basin extended also into Newfoundland and probably drained northeastward into the Atlantic.

Varied Conditions in the West

The rising mountains in Oklahoma and Colorado (see below) introduced varied conditions in the western states. At times of greatest submergence they stood as islands in the sea, and even when the sea was far away they were flanked by structural basins in which nonmarine sediments accumulated over wide alluvial plains. A marine embayment persisted throughout much of the period over parts of Utah and Nevada.

Crustal Unrest

Uplift and mountain making were not confined to the beginning and the end of this period; it was, throughout, a time of much crustal warping and of repeated local disturbances, with folding in the marginal lands and in the Mid-Continent as well. This we know from the character of the sediments. If Appalachia had remained stable, the basal conglomerates of the Appalachian basin should have given way to finer and finer sediments as the relief of the highlands was brought low. Such, however, is not the case, for sandstones alternate

with shales and locally give way to conglomerates in the upper as well as the lower part of the system. Limestones are rare, thin, and usually impure east of the Mississippi River. Without repeated rejuvenation, the borderlands could hardly have supplied the enormous thickness of the formations, which nearly everywhere exceeds 3000 feet, amounting to 9000 feet in Alabama, more than 20,000 feet in Arkansas, 15,000 feet in Oklahoma, and 13,000 feet in Nova Scotia.

The Acadian Highlands. In the Maritime Provinces of Canada there are five unconformities in the Pennsylvanian succession, each corresponding to local uplift. Here the depositional basins were intermont troughs produced by block faulting. In some places this movement involved only broad regional warping, but in others even the sediments in the basin were locally folded. Farther south no particular episodes of deformation have been determined, but in Alabama it is evident that Appalachia stood almost as high throughout the Pennsylvanian as it did at the beginning of the period.

Uplift in Llanoria; The Oklahoma Mountains. During the closing stages of the Mississippian period or, more likely, at the very beginning of the Pennsylvanian (depending on the age of the Stanley-Jackfork deposits of Arkansas and Oklahoma), there was marked uplift in Llanoria, whence rapid erosion brought a vast amount of detrital material into the Ouachita geosyncline. As if to compensate for this uplift, the geosyncline subsided steadily and so formed a trap to catch the sediments which accumulated to a thickness of more than 15,000 feet (23,000 feet in Arkansas) during the period.

During the initial phases of this movement the deformation and uplift were wholly in the land mass south of the geosyncline, where compressive forces were exerted from the region which is now the Gulf of Mexico. But at a later stage, still early in the Pennsylvanian period (Atoka time), the floor buckled along the northern margin of the geosyncline to form a series of ranges of domed mountains along the southern border of Oklahoma and across the Panhandle of Texas. These have been named the *Oklahoma Mountains*. They include the Arbuckle and Wichita mountains of Oklahoma and the buried Amarillo Mountains of Texas (Fig. 155). They arose out of the Pennsylvanian sea as rather simple arches accompanied by numerous normal faults. Suffering active erosion as they rose, they were flanked by their own debris, while the downwarped areas about them trapped the sediment that continued to pour into the geosyncline from the hinterland, Llanoria. Their topographic relations were thus some-

what like those of the mountainous Shantung peninsula, which now rises out of the surface of the great Hwang-Ho delta in China.

These ranges probably did not attain a great height above the sea, but they were repeatedly uplifted as they were eroded, and the floor immediately adjacent continued to sink, until Pennsylvanian formations accumulated which still are more than 12,000 feet thick in the Ardmore basin just south of the Arbuckles and also in the Anadarko basin to the north. If these strata were now stripped away, the Arbuckles would tower above their base as a range of mountains more than 2 miles high. They never stood so high above the surrounding surface, however, because the adjacent area was subsiding while they rose and they were largely buried in their own debris. The history of the Wichita and the Amarillo mountains is essentially similar. They are approximately parallel to the Arbuckles and are related in time and in structure. It now appears that there were at least two major pulses in their uplift, one early in the Pennsylvanian and another near the middle of the period.[1]

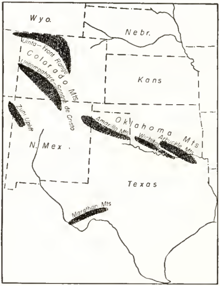


Fig. 155. Sketch map showing the location of late Paleozoic mountains in the Mid-Continent region. Data in part from Ver Wiebe, from Powers, and from P. B. King.

The Colorado Mountains. Throughout Pennsylvanian and Permian times, as well as in the early Mesozoic, a group of uplifted areas in Colorado and near-by states profoundly influenced the formations deposited in the Rocky Mountain region. The Pennsylvanian formations are thick and almost entirely detrital near these old ranges, becoming finer grained and more calcareous in all directions from the uplifted areas. It appears evident that these ranges were of mountainous height or were repeatedly uplifted in order to supply the great bulk of detrital sediments that flank them. At least four orogenic

units are recognized and individually named (Fig. 155). The entire group has been designated the *Colorado Mountains.**

Marathon Disturbance and the Close of the Period. Near the close of the period a range of fold mountains was thrust up out of the sea in western Texas, accompanied by northward thrusting that car-

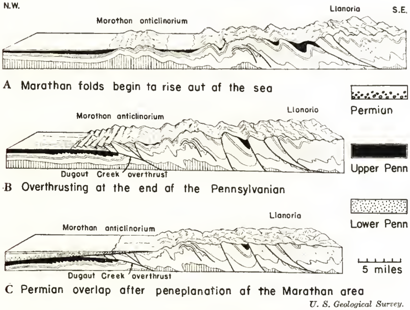


FIG. 156. Three stages in the history of the Marathon orogeny. The section runs from northwest to southeast across the Marathon folds and includes a part of Llanoria, the Paleozoic land mass that has since been reduced by erosion and buried under the Cretaceous deposits of the Gulf Coastal Plain. Adapted from Philip B. King.

ried Devonian and Ordovician formations up over the Pennsylvanian. These structures are now clearly exposed in the Marathon basin of

* The name *Ancestral Rockies* was introduced for these mountains by Willis T. Lee in 1918 and has since gained considerable usage. It unfortunately carries a connotation of genetic relation to the present Rockies that is not justified. These Paleozoic structures differed in their trend from the modern ones and were later submerged and deeply buried during the latter half of Mesozoic time. The forces that built the Rockies were probably unrelated in genesis and certainly separated by a hundred million years or more in time from those responsible for the Paleozoic mountains. Our experience has shown that the use of Lee's name invariably leads to confusion of the true relations, and in 1933 we therefore proposed the geographical name *Colorado Mountains,* since the uplifts were largely (though not entirely) confined to that state.

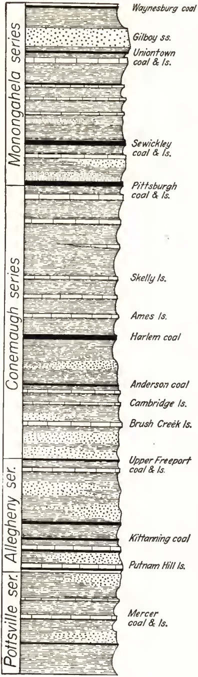
Trans-Pecos Texas, and the disturbance has been named for this region (Fig. 156).

The Marathon area was within the Ouachita geosyncline during Pennsylvanian time, and the very thick record of this period shows that marked uplift occurred repeatedly in Llanoria a short distance to the south. For example, there are numerous beds of conglomerate in the Marathon basin, some of them of exceptional coarseness, containing rocks that could only have come from the near-by south. It was not till the close of the period, however, that the compression reached northward with such force as to crumple and close-fold the rocks of the geosyncline. As a result of this disturbance, the Pennsylvanian and older formations were folded, faulted, and uplifted, and later were truncated by erosion so that here the Permian strata overlie them with profound unconformity. The disturbance was less intense to the north and west of this area, but an angular unconformity is common between the Pennsylvanian and Permian as far west as El Paso. Most of the disturbed area in Texas is now covered by Cretaceous rocks.

Close of the Period

Near the close of the Pennsylvanian there was a marked retreat of the interior sea toward the west, and the continent was largely if not completely emergent for a time. Western Texas and southern New Mexico were then in the throes of the Marathon orogeny, but over much of the Central Interior the late Pennsylvanian emergence was due to continental uplift which resulted merely in nondeposition with no marked deformation in the Pennsylvanian deposits. As a result, great difficulty has been experienced in drawing an exact boundary line between the Pennsylvanian and the Permian systems in parts of the United States.

In various parts of the world, however, there was extensive orogeny at this time (Fig. 147). The Armorican ranges of Europe, initiated at the end of the Mississippian, experienced marked rejuvenation during and at the close of the Pennsylvanian. In fact, the culmination of Late Paleozoic mountain making occurred at this time and during the Early Permian. The effects of this orogeny are to be seen in the stumps of the ancient mountains in southern Wales and England, in the central plateau of France, in the Harz and Black Forest regions of Germany, and in Bohemia; likewise in the Spanish Meseta, Corsica, and Sardinia. In the Himalaya region, this was a time of great mountain making, "a great revolution in the physical geography of India," which during Pennsylvanian time blotted out the inland



(Tethyan) sea. In the Urals also, as in eastern Australia and the Andean region, there was disturbance at this time. In most parts of the world, however, the areas of Late Pennsylvanian orogeny suffered even greater disturbance during or at the close of the Permian.

Stratigraphy of the Pennsylvanian System [2]

Appalachian Coal Fields. In the Appalachian basin, sandstones and shales make up nearly the entire thickness of the Pennsylvanian formations, though conglomerates occur at various levels, especially near the eastern margin (Fig. 157). The sandstones and conglomerates are commonly lenticular and cross-bedded, lensing in and out among the shales so that it is usually difficult to follow a definite horizon for many miles. The color is generally gray or dark because of the carbon of included organic matter, though in some places redbeds alternate with the gray. The dark sediments include abundant remains of land plants. Coal beds occur at many horizons, some of them thick enough to mine, others not. It is evident that these sediments were deposited by streams on a swampy lowland. At occasional intervals, however, there are

Fig. 157. Section of the Pennsylvanian system in eastern Ohio (Muskingum County), showing repeated alternations of coal, sandstone, shale, and thin limestone. Vertical scale 1 inch = 150 feet.

W. A. BELL, GEOLOGICAL SURVEY OF CANADA.

Fig. 158. Fossil tree trunks standing as they grew. Specimen at the left, from The Joggins, Nova Scotia; that at the right, showing 8 feet of trunk, from Table Head, Great Bras d'Or, Cape Breton.

thin beds of impure limestone or of calcareous shale, bearing marine fossils, which represent temporary inundations of the lowlands by the sea. The marine limestones, though thin, are persistent over large areas in contrast with the varied fluvial deposits. They form important key horizons for correlation and the determination of structure. In general, they are most numerous, most regular in sequence, and of widest spread in the western part of the basin, for they tend to wedge out and disappear toward the east.

In the coal basin of Nova Scotia and New Brunswick, where the Coal Measures reach a thickness of a few thousand to 13,000 feet, marine horizons are wholly absent. The section exposed in the sea cliffs at The Joggins near the head of the Bay of Fundy is of special interest because of the stumps and trunks of trees buried in the position of their growth (Fig. 158). Here erect trunks are recorded at 20 horizons distributed at intervals through about 2500 feet of beds. Many of the preserved trunks are several feet high, some exceeding 20 feet. They show clearly how rapid the deposition of individual beds must have been, since they were in each case buried before the stumps had time to decay. It is evident, however, that deposition

of sediment at any locality was intermittent, since these trees, some of them as much as 4 feet in diameter, must have grown unhindered before their burial. Deposition appears to have been by sluggish, meandering streams that frequently deserted their sediment-choked channels to burst out in new courses over timbered lowlands. (Compare Fig. 27, p. 46.)

Illinois Coal Fields. The Illinois field is closely allied to that of the Appalachian basin. The two were originally continuous in the southern part and shared in common deposition, but have since been isolated by later uplift and erosion along the Cincinnati arch. In general, the sediments are finer of grain in Illinois, and marine shales assume much greater importance than in the East. There are a number of widespread coal beds, however, some of which appear to have extended over most of the state and eastward into Indiana. A limestone "cap rock" occurs a short distance above nearly every one of the coals; these vary in thickness from several inches to a few feet and are as widely persistent as the coal beds, the repeated occurrence of these marine horizons above the coals emphasizing the cyclic nature of the deposition in this region. Each coal is the residue of vegetation that grew here while the region stood as a swampy lowland. The cap rock of limestone shows that the sea followed, inundating the swamp. Marine shales follow the limestone, grading up into nonmarine shales and sandstone that were formed as the sea was filled up and driven back. Local unconformities occur at the horizon of the transition, marking places where the extended streams cut channels in the shale and filled them with sand.

Mid-Continent Region. The coal fields of Missouri and Kansas, like those of adjacent parts of Nebraska and Iowa, present a section of 2000 to 3000 feet of beds in which limestones and shales alternate repeatedly, while sandstones and siltstones occur at greater intervals (Fig. 159). Here the limestones comprise about 25 per cent of the section and sandstones generally less than 10 per cent. Many of the shales and siltstones bear no fossils except fragments of land plants, and were probably deposited on low delta plains. The limestones, on the contrary, like certain of the shales, have abundant marine fossils. In this region many of the thin units persist with little change over great distances, bearing witness to uniform conditions of deposition over great areas. Repeated alternations of marine and nonmarine beds indicate that deposition was approximately at sealevel and suggest that the marine waters were extremely shallow.

Traced southward into Oklahoma and Arkansas, the entire system changes gradually but profoundly as we enter the Ouachita geosyncline and approach Llanoria. There the section thickens to 12,000 or even 23,000 feet; sandstones and siltstones assume great prominence, while the limestones thin and in many cases grade laterally into sandstone or shale. In short, the thickness of the Coal Measures in the Ouachita geosyncline is fully five times that of the northern Mid-Continent fields. This has resulted in part from the more rapid deposition in the geosyncline where subsidence allowed the sediment to come to rest, in part from the nearness to Llanoria, which was supplying much of this material, and in part from the fact that deposition began first in the geosyncline and gradually overlapped northward.

Carl O. Dunbar.

Fig. 159. Oread formation, consisting of alternating members of limestone and shale, at Lawrence, Kansas. A characteristic outcrop of the Pennsylvanian strata in the Mid-Continent region.

In central and western Texas the Pennsylvanian formations are several thousands of feet thick, and here also the influence of Llanoria may be seen.

Deep drilling has shown that Pennsylvanian formations extend west of their outcrop under nearly all the Great Plains. They are exposed in the Black Hills and in the hogbacks flanking the front of the Rockies, as well as about many of the ranges farther west.

Cordilleran Region. Throughout the Cordilleran region there is so much local variation that brief description is impossible. Along the front of the Rockies, in Wyoming and Colorado, where these formations overlap on Pre-Cambrian granite, the lower part (Fountain formation) is arkosic and red. The upper part also (Lyons formation) is largely red and generally sandstone and shale. In the vicinity of Colorado Springs these rocks are much cross-bedded, unfossiliferous, and wholly nonmarine. but toward the northeast they

grade in part into calcareous and marine deposits (Ingleside of Wyoming and Minnelusa of the Black Hills). Farther west in Colorado, also, there are fossiliferous marine sections. In northeastern Utah is the Oquirrh formation, with the astonishing thickness of more than 15,000 feet of lenticular quartzites and limestones, and but little shale. The lower several thousand feet of this deposit is of Pennsylvanian age, but the upper part is Permian. In extreme western Colorado and east-central Utah the Paradox formation, supposedly of Pennsylvanian age, includes a great thickness of *salt*, which apparently interfingers laterally with dolomite. Here is striking evidence of local aridity that stands in marked contrast with the coal swamps of the East. It may represent a local condition in the rain shadow of the western range of the Colorado Mountains.

The great amounts of detrital sediment and the local variations in the Pennsylvanian rocks of the Cordilleran region stand in striking contrast with the far-flung limestones of the underlying system and bear witness to the disturbances that began in this region about the close of Mississippian time.

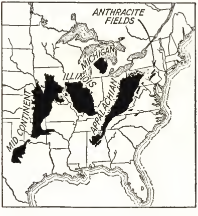


Fig. 160. Map showing the coal fields of Pennsylvanian age in eastern United States.

Economic Resources

Coal. It is no accident that in many parts of the world the Pennsylvanian rocks are known as the "Coal Measures." Although coal has formed locally during every period since the spread of terrestrial vegetation in the Devonian, no other system contains so much *high rank* coal. In these formations lie the great coal fields of the British Isles, of France (Saar basin), of Germany (Ruhr basin), and the smaller fields of Belgium and Silesia, and of the Donetz basin of Russia; likewise the chief coal fields of North America. These fields, together, produce more than 80 per cent of the world's coal. Some of the younger systems (Jurassic and Cretaceous) may hold even greater reserves for the future, but the younger coals are generally inferior in quality and can not extensively compete with the Paleozoic coals in the world markets.

In America the coal fields of Pennsylvanian age occupy an area estimated to exceed 250,000 square miles, a figure considerably greater than that of the coal fields of any other continent. They lie almost entirely in the eastern half of the United States, the chief exception being the small Acadian basin of the Maritime Provinces of Canada (Fig. 160).

FIG. 161. Coal fields of Pennsylvania. The anthracite fields (*vertically lined*) are synclines in the folded zone. The bituminous fields (*horizontally lined*) are in the flat-lying rocks of the Allegheny Plateau.

Of the five well-defined fields shown in the figure, the *Anthracite field* of eastern Pennsylvania is in some respects the most interesting. Although less than 500 square miles in area, it has produced to date almost one-fourth of the total output of coal in North America. Its production reached a peak of 93,000,000 tons in 1923 and has averaged over 85,000,000 yearly for the last quarter-century. Unfortunately more than half of the coal has already been mined, and the supply of anthracite bids fair to be exhausted during the life of the present generation.

The anthracite field is in reality but an eastern part of the vast Appalachian basin that was caught in the Permian folding, and isolated from the rest by later erosion that destroyed all the Coal

Measures in eastern Pennsylvania except those parts preserved in deep synclinal folds (Fig. 161). This folding and the resulting pressure converted the bituminous coal into the hard anthracite by eliminating the volatile matter. The thickness of some of the anthracite beds is noteworthy. The most remarkable bed is the Mammoth, which extends throughout the field, with an average thickness of 35 to 40 feet and in one place a thickness of 114 feet due to overfolding (Fig. 162).

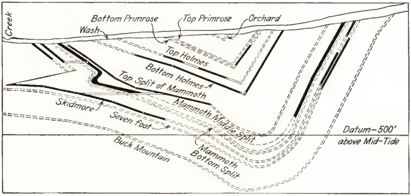


FIG. 162. Cross-section of a fold in the South Anthracite coal basin, after Kemp. The Mammoth coal bed is separated by interbedded shale into 3 distinct beds, each known as a "split" of the Mammoth coal.

The *Appalachian field* is the second largest, and much the greatest producer of the several coal regions. It underlies the Allegheny Plateau and extends from northern Pennsylvania to Alabama. Pennsylvania and West Virginia are the heaviest producers, but Ohio, Kentucky, and Alabama also yield much coal. This field alone furnishes almost one-fourth of the world's coal supply.

Throughout most of this area the strata lie quite flat, and the coal is bituminous, occurring at many levels. About 60 beds are recognized in Pennsylvania, but of these only 10 are widely mined, the rest being too thin to work profitably. The most remarkable of these beds is the Pittsburgh coal (Fig. 163), which is more than 13 feet thick about Pittsburgh and is known to be workable over an area of 6000 square miles in western Pennsylvania, eastern Ohio, and northwestern West Virginia, where it is estimated to contain more than 22,000,000,000 tons of coal. Up to 1926 it had yielded approximately 3,500,000,000 tons of coal, with a value at the mines more than twenty times that

of the gold produced by the greatest gold mine in the United States.[3]

The *Illinois field* is a shallow structural basin extending into southwestern Indiana and western Kentucky. It includes 10 or more important producing horizons and ranks second to the Appalachian field, far outstripping the much larger Mid-Continent region in production. The coal beds here do not attain so great a thickness as they do farther east, but some of them, notably the Herrin coal, persist with remarkable uniformity over much of the state of Illinois.

The *Mid-Continent field* embraces the coal fields of Missouri, Iowa, Kansas, Oklahoma, and northern Texas. Although the area exceeds that of the Appalachian field, the output of coal has been less than one-tenth as great. Here the beds are commonly less than 4 feet thick, and the best producing horizons are in the lower part of the system. There are extensive areas where the surface is flat and the

U. S. BUREAU OF MINES, PITTSBURGH.

Fig. 163. Outcrop of the Pittsburgh coal seam near Pittsburgh, Pennsylvania.

coal so near the surface that it is mined by stripping with steam shovels.

The remaining fields are relatively small producers, together supplying less than 1 per cent of the world's coal. In the tiny Rhode Island basin extreme metamorphism has reduced the coal to graphite, or so nearly so that it has little fuel value.

Most of the Pennsylvanian coals of the United States include sulphur as an impurity. This is believed to indicate that the coal swamps bordered the inland seas and were brackish, since sulphur-depositing bacteria live in the sea but do not thrive in fresh-water lakes and swamps. Conversely, the slight amount of sulphur in the anthracite of eastern Pennsylvania and in the coals of the Acadian basin indicates for these regions swamps entirely of fresh water.

Petroleum and Natural Gas. Pennsylvanian rocks have been an important source of petroleum and natural gas in the Mid-Continent oil fields, and for a number of years, from the discovery of these fields in the 1890's until about 1925, constituted their only important producing horizon. During that time Kansas and Oklahoma produced from these beds over 2,000,000,000 barrels of oil. Subsequently, however, production has been found at greater depths in the Ordovician "sands," which have given the spectacular developments of recent years in those two states and in north-central Texas.

Climate

The terrestrial sediments with their plant remains speak eloquently of warm, moist climate during the chief coal-producing stages of the Pennsylvanian in many parts of the world. The vegetation of the coal beds clearly grew in swamps, where it accumulated under standing water, as evidenced by the spreading root systems still preserved in the fire clays that underlie the coals in many places. Moreover, the structural types of the foliage so well preserved in the roofing shales at many places indicate marked humidity. Swamp waters are required to protect the fallen vegetation from the air and thus save it from decay. The wide distribution and the repeated occurrence of coals therefore assure us that there was a persistently moist climate over vast regions of the Pennsylvanian landscape.

This does not prove, of course, that no parts of the Earth were arid. It is well to remember that at present the dripping jungles of the Amazon Valley are separated only by the narrow Andean chain from

the desert coast of western Peru. Similar extremes probably existed on the continents during Pennsylvanian time, for lofty mountains must have been accompanied, then as now, by a leeward rain shadow of deficient rainfall. The salt deposits of the Paradox formation in eastern Utah and western Colorado, like the red arkose of the Fountain formation of central Colorado, may indicate such local aridity about the Colorado Mountains. On the contrary, the coal swamps of the eastern interior were formed where the warm, moist winds were rising up the long western slope of Appalachia. In general, it appears that humid climatic conditions were exceptionally widespread during Pennsylvanian time.

There is also much evidence that the climate was warm, even in high latitudes, during much of the period. The mere presence of abundant vegetation is no evidence, for it is well known that the most extensive modern accumulation of peat is in subarctic regions where slow growth is more than counterbalanced by slow decay; but the *character* of the Carboniferous vegetation indicates a lack of freezing winters, at least in the lowlands where the plants are preserved. The trees, whether tree ferns, seed ferns, cordaites, or the great scale trees, bore succulent foliage of almost unprecedented luxuriance. Not merely were the leaves large, but their texture indicates rapid growth under warm, humid conditions. For example, the very large size of the individual cells, the arrangement of the stomata (breathing pores), the smoothness and thickness of the bark, the presence of aerial roots, and the absence of growth rings in the woody trunks are all features of significance. One of the foremost paleobotanists of our times concluded that "the climate of the principal coal-forming intervals of the Pennsylvanian was mild, probably nearly tropical or subtropical, generally humid, and equable." [4]

The animal life of the time also seems to support this view. Insects, for example, attained an extraordinary size and, so far as known, averaged larger than in any other period of Earth history. Since it is well known that the modern orders of insects have their large representatives in the tropics, with smaller and smaller species in regions of more rigorous climate, the significance of the Pennsylvanian insects is obvious. To this may be added the fact that at certain times during the period corals were able to thrive in great abundance and to form reefs as far north as the arctic islands of Spitzbergen (lat. 78° N.). The presence of these ancient reefs in the sea cliffs of a land now treeless and ice-covered speaks eloquently of the climatic contrast between

the present and the Pennsylvanian age in this region (Fig. 164). The exceptional abundance of the large fusulines in the limestones of the northern hemisphere, and even as far north as Spitzbergen, seems to have a significance like that of the insects.

Nevertheless, we must not assume that all parts of the world were warm. Great changes have occurred in the temperature of most of the

O. Holtedahl.

FIG. 164. Coral reef in the Early Pennsylvanian (Moscovian) deposits of western Spitzbergen. Both tetracorals (*Campophyllum*) and tabulates (*Chaetetes*) contribute to the deposit. The present arctic climate is indicated by the snowbank at the left.

lands in the few tens of thousands of years since the Pleistocene ice age. During a period like the Pennsylvanian, of millions of years' duration, there may have been important fluctuations in the world climate.

The extensive continental glaciation of India, South Africa, South America, and Australia, which some geologists attribute to Late Pennsylvanian time, we regard as of Permian age. It is discussed in Chapter 13.

Without a doubt the polar regions were cooler than those of low latitudes, and it may well be that the mild climate of Spitzbergen was due to the local influence of a warm ocean current which then streamed into the Arctic. Nevertheless, the evidence for mild climate is so

widespread that we can not avoid the belief that in general the Pennsylvanian was an exceptional period in the climatic history of the Earth.

Life of the Pennsylvanian Period

Forests of the Swamp Lands

Forests of fast-growing, soft-tissued trees, tangled in dense undergrowth, spread over the moist lowlands of the Pennsylvanian landscape. Among these were none of the deciduous forms like those of our modern forests, for they had not yet evolved. The giants of the time were strange, spore-bearing trees which today are represented only by insignificant, herbaceous descendants like the ground pines and scouring rushes (Fig. 165).

Under the moist and perpetual summer of the coal swamps, shades of green must have been dominant. It is likely that the monotonous verdure was rarely enlivened by bright colors, for the primitive flowers of the time were simple and doubtless small as a rule. There was probably no honey to lure the insects and no sweet perfumes to scent the air, only fresh resinous odors such as pervade the living conifer forests.

Although seed-bearing plants were common, spore-bearing trees were even more abundant and at certain seasons must have covered the forests with a greenish yellow or brownish dust of spores, since some of the coals (cannel coal) are composed almost entirely of spore cases.

Ferns of many kinds were common, and they alone gave a modern aspect to the dells of these ancient forests. The leaves of some species attained huge proportions, single fronds reaching a length of 5 or 6 feet; and the slender, unbranched trunks grew to be as high as 50 feet.

Seed ferns resembled the true ferns in every respect save one: they bore small nutlike seeds instead of spores appended to their fronds. They may have descended from ferns and in turn may have given rise to all the higher, seed-bearing plants. They were more common than the true ferns in Pennsylvanian time and have often been confused with them, since the two groups can be distinguished only when fruiting fronds are found.

Scouring rushes of giant size grew in solid stands like "cane brakes" in portions of the swamps. Like their humbler modern descendant, *Equisetum*, they are easily recognized by their vertically ribbed and regularly jointed stems (Figs. 165, 166). The Paleozoic forms bore

YALE PEABODY MUSEUM.

Fig. 165. A Pennsylvanian landscape showing characteristic animals and plants. Part of a great mural by Rudolph Zallinger. Plants: 1, a tree fern; 2, Lepidodendron, a scale tree; 3, Sigillaria, a scale tree; 4, Cordaites, a precursor of the conifers; 5, Calamites, a giant scouring rush. Animals: 6, Diplovertebron; 7, Eryops; 8, Eogyrinus; 9, Seymouria; 10, Limnoscelis; 11, Meganeuron, a giant dragonfly. Numbers 6–8 are amphibians; numbers 9–10 are reptiles.

at each joint a whorl of slender simple leaves which in modern rushes are represented only by bractlike vestiges. The leaf whorls, known as *Annularia,* commonly present a false resemblance to flowers. The largest of the Pennsylvanian rushes belonged to the genus *Calamites.* Some of these exceeded 12 inches in diameter and had a height of 30 or more feet. Their trunks were not solid woody stems but rather thin woody cylinders filled with a core of pith and surrounded by thick bark, the woody layer seldom having a thickness of 2 inches.

The *scale trees* were the most imposing plants of the forests and in many places the most common. Their name is derived from the fact that their close-set leaves left permanent leaf scars over the trunk and

limbs that make them appear scaled (Figs. 166, 167). So striking is this deception that twigs have been mistaken by amateur fossil hunters for petrified snake skins. The scale trees grew to a large size, their stumps reaching a diameter of 4 to 6 feet and their slowly tapering trunks an extreme height of more than 100 feet. Most of them belonged to one of two well-defined types, *Levidodendron* or *Sigillaria.*

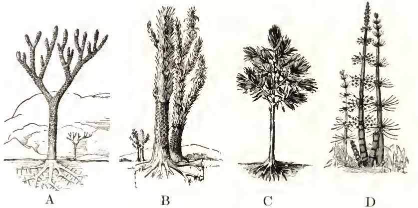


FIG. 166. Coal Measures plants. A, *Lepidodendron;* B, *Sigillaria;* C, *Cordaites;* D, *Calamites.*

Lepidodendron (Figs. 165, 166) grew a tall slender trunk branching repeatedly near the top to present a spreading crown of stubby twigs covered with slender straplike leaves. These leaves, like immensely overgrown pine needles, in some species were 6 to 8 inches long and ½ inch wide. The older leaves were shed as new ones formed at the tips of the branches, leaving sharply defined diamond-shaped leaf scars which were normally arranged in spiral rows about the limbs and the trunk (Fig. 167). The branching was normally dichotomous (with equal forks). Spore cases were borne as cones at the tips of the limbs.

Sigillaria (Figs. 165, 166) possessed a thicker trunk which rarely branched and was clothed for several feet from the top with large bladelike leaves, resembling those of *Lepidodendron* but larger. In these trees the bark was vertically ribbed, and the leaf scars were normally in vertical rows. Trunks have been found with a diameter, just above the roots, of 6 feet, and one specimen is known to be 100 feet long without a branch.

About 100 species each of *Sigillaria* and *Lepidodendron* have been described. Although many of them were large trees, some were relatively small. In all of them the structure of the trunk and limbs was peculiar in that they had a relatively large center of pith surrounded by a woody cylinder, and this in turn by two very thick layers of corklike bark. The leaf scars are impressed only on the bark. The root system likewise was peculiar, the main trunk roots spreading almost horizontally without a tap root; moreover, they branched but a few times and so were stubby and thick. The real rootlets sprang directly from the sides of these trunk roots, radiating thickly away to a distance of several inches. Such root stocks, known as *stigmaria*, are common in the fire clays under coal beds and not infrequently appear in the coal.

Yale Peabody Museum.

FIG. 167. A bit of the bark of the scale tree, *Lepidodendron nodulatum*, showing the characteristic leaf scars. Slightly less than natural size.

The *cordaites* (named after the Bohemian botanist Corda) were the forerunners of the modern conifers, which they resembled in their sturdy soft-wood trunks and their parallel-veined leaves (Figs. 165, 166). They differed from true conifers in two chief regards: (1) their leaves were not needlelike but bladelike, attaining a length of several inches to 5 or 6 feet, and (2) their seeds were borne in racemes instead of being crowded into cones. Many of them were tall, graceful trees, some attaining a height of 120 feet and a diameter as great as 3 feet. In such trees fully two-thirds of the trunk was without branches, though the top was a dense crown of branches and large simple leaves. The wood of the cordaites was much like that of modern pines, but the pith at the center was larger. They appear to have been one of the chief contributors to the vegetation that made the Pennsylvanian coal.

It is obvious that our knowledge of the Pennsylvanian land plants relates almost wholly to the swampy lowlands. Possibly the most rapid advances were being made in the uplands, where the climate was more rigorous and more stimulating but where the chances for preservation of the record were slight.

One of the striking features of the Pennsylvanian floras is the marked similarity of the species in different parts of the world. They were as nearly *cosmopolitan* as any in the Earth's history. This must mean that their migration from one continent to another was favored by extensive land connections and by freedom from climatic barriers.

The Animal Conquest of the Lands

Through the dank forests of Pennsylvanian time droned clumsy, primitive insects, while centipedes, spiders, and scorpions scurried

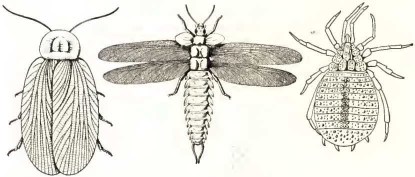


FIG. 168. Pennsylvanian insects and a spider. Left, a cockroach, *Aphthoroblattina johnsoni;* center, a primitive insect, *Stenodictya lobata;* right, a spider, *Eophrynus prestwichii.* Natural size. In part after A. Handlirsch.

about over the fallen logs in search of food. Small land snails worked their tedious way in the trees, and in the swamps a hundred or more kinds of sprawling amphibia lolled about as do crocodiles or giant salamanders (Fig. 165). Before the close of the period the more adventurous of these amphibians had left the water permanently to establish the dynasty of the reptiles. Now for the first time we find the record of varied and abundant land animals; henceforth their dominion over the lands is never for a moment in doubt.

The *insects* of this time were truly remarkable for their great size. Out of four hundred forms known from Lower and Middle Pennsylvanian strata, more than a score exceeded 4 inches in length, six attained to nearly 8 inches, and three exceeded a foot, the average length being about 2 inches. The largest of all was a dragonfly-like type found in the Coal Measures of Belgium, which had a wing spread of 29 inches (Fig. 165). No period since has produced insects so large.

Most of these insects were of strange primitive stocks not exactly like any of the modern orders. Cockroaches, however, were very like the living ones, only larger, and so common that the period has sometimes been called the *Age of Cockroaches* (Fig. 168). Several of the Pennsylvanian species achieved a length of 3 or 4 inches.

FIG. 169. *Pelion lyelli*, a probable ancestor of the modern frogs. Specimen imbedded in shale, its back down. Lower middle Pennsylvanian shale at Linton, Ohio. Natural size. Original in the American Museum of Natural History. From Roy L. Moodie, by courtesy of the U. S. National Museum.

The presence of several hundred species of insects in the Pennsylvanian makes their sudden appearance at this time the more remarkable. The diversity of the forms represented implies a long antecedent evolution whose record may yet be found in Mississippian if not in Devonian rocks.

Scorpions, remarkably like modern ones in size and structure, occur with the insect fossils. *Spiders* (Fig. 168) likewise occur, though none of the fossils shows clear evidence of spinnerets, and it may be that these early forms did not make webs. *Centipedes* (or myriapods) of several kinds are known, the largest of which, found at Mazon Creek, Illinois, had a length of 12 inches.

Land snails were first discovered in the famous Joggins section of Nova Scotia, where they were associated with the skeletons of amphibia. Both had taken refuge in standing hollow stumps that were overwhelmed by floods and buried by sand and mud. Land snails are extremely rare fossils in the Paleozoic rocks, however, and all are small.

Small *fresh-water clams* of several kinds (*Carbonicola, Anthracomya*, etc.) occur abundantly in the dark shales of certain of the coal fields, especially in Nova Scotia and Europe.

Vertebrate animals are represented by abundant skeletal remains of *amphibia.* From the Coal Measures of North America alone no fewer

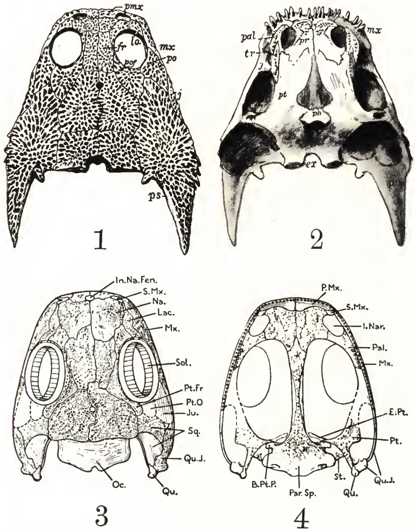


FIG. 170. Skulls of Pennsylvanian labyrinthodonts. 1, 2, *Diceratosaurus* (dorsal and ventral views) from Linton, Ohio (natural size); 3, 4, *Miobatrachus* (dorsal and ventral views) from Mazon Creek, Illinois ($\times 2\frac{1}{4}$). After Moodie and Watson, respectively.

than 7 orders, 19 families, 46 genera, and 88 species are known. Such great diversity suggests that these animals were common in spite of the fact that they are still the rarest of fossils. The most remarkable single locality for such remains is at Linton, Ohio, at the base of the Freeport coal, where abundant ganoid fishes and no fewer than 50 species of amphibia have been found (Figs. 165, 169, 170).

Fig. 171. A primitive salamander (*Eumicrerpeton parvum*), less than 2 inches in length, as reconstructed by Roy L. Moodie from specimens found in concretions in the Pennsylvanian shales at Mazon Creek, Illinois.

The Pennsylvanian amphibia were labyrinthodonts, and nearly all were small (Fig. 171). Many of them were only a few inches long, and large ones, scarcely 10 feet over all, would not exceed a large Florida alligator. The greatest of all is known only from its tracks, deeply impressed in Mid-Pennsylvanian sandstone near Lawrence, Kansas. This animal (*Onychopus gigas*) had blunt, stubby feet over 5 inches long, and although its stride was only about 30 inches, the right and left treads were wide apart, indicating a short but very heavy-bodied animal estimated to weigh not less than 500 or 600 pounds. There is some evidence that the feet were webbed like those of a crocodile.

A few *reptiles* of small size appeared during the later half of the period, but their remains are very rare (Fig. 172).

Résumé of the Marine Animals

The invertebrate life of the Pennsylvanian seas was not only prolific but also varied. Moreover, it was a cosmopolitan assemblage, presenting much the same aspect in various parts of the world.

Brachiopods (Pl. 10, figs. 1–6, 8–12) and *lacy bryozoa* continued in great profusion. The spiny productids exceeded all other brachiopods and gave a distinctive aspect to all the faunas.

The muddy and sandy sea floors seem to have been especially suitable for *pelecypods* (Pl. 10, figs. 18–22) and *gastropods* (Pl. 10, figs. 14–17), which were represented by hundreds of species. In general, these were still small, however, few of the shells exceeding a length of 1 or 2 inches. *Cephalopods* were much less numerous and generally

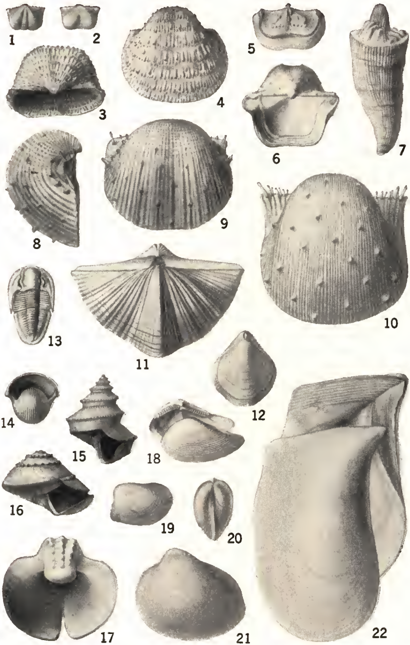


Plate 10. Pennsylvanian Brachiopods (1–6, 8–12), Coral (7), Trilobite (13), and Molluscs (14–22).

Fig. 1, *Mesolobus mesolobus;* 2, *Lissochonetes geinitzianus;* 3, 4, *Juresania nebrascensis;* 5, 6, *Marginifera splendens* (5, interior view of dorsal valve); 7, *Lophophyllum profundum;* 8, 9, *Dictyoclostus portlockianus;* 10, *Linoproductus prattenianus;* 11, *Neospirifer dunbari;* 12, *Composita subtilita;* 13, *Phillipsia major*, one of the very last of the trilobites; 14, *Euphemites carbonarius;* 15, *Worthenia tabulata;* 16, *Trepospira sphærulata;* 17, *Pharkidonotus tricarinatus;* 18, *Nuculana arata;* 19, 20, *Nuculopsis ventricosa;* 21, *Schizodus wheeleri;* 22, *Myalina subquadrata.* All natural size. Drawn by L. S. Douglass.

are poorly preserved, though in some regions, especially the coal fields of Europe, they are not so rare and are of great value in stratigraphic correlation. Of these, the nautiloids were rather on the decline, but the *goniatites* were rapidly changing into a variety of forms and developing more complicated sutures, foreshadowing the expansion of the typical ammonites during the next period.

U. S. National Museum.

Fig. 172. The oldest known reptile, *Eosauravus copei.* The hind legs and most of the backbone are preserved. Lower middle Pennsylvanian beds at Linton, Ohio. Natural size. From Roy L. Moodie, by courtesy of the U. S. National Museum.

Corals (Pl. 10, fig. 7) of a few kinds, mostly solitary types, persisted, but only locally assumed importance. Echinodermata are represented by abundant *crinoidal* fragments and the plates and spines of *sea-urchins,* but well-preserved skeletons of either group are not common because the shallow sea floors were wave-swept enough to break apart the echinoderm bodies. *Blastoids* made their last stand in the earliest part of the period and are never found above the lowermost Pennsylvanian formations (Wapanucka and Morrow), except in the East Indies, where several genera appear in the Permian.

One of the most striking groups of Pennsylvanian fossils is the *fusulines,* a family of relatively large bottom-dwelling Foraminifera. They built multichambered limy shells of globular or fusiform shape, whence the name Fusulinidæ, meaning spindle-shaped. Commonly they resemble grains of wheat or oats in size and shape. They were important rock makers in many parts of the northern hemisphere, where fusuline limestones are widely spread (Fig. 173).

Small foraminifers were also common and varied in the Pennsylvanian seas. Ostracods were still numerous though nearly all very small.

Minute types of fossils, such as foraminifers and ostracods, have proved to be very useful in subsurface correlation in the oil fields,

FIG. 173. Fragment of fusuline limestone from the Upper Pennsylvanian of Kansas Natural size.

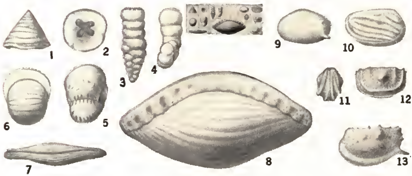


FIG. 174. Microfossils from the Pennsylvanian, greatly enlarged. Foraminifera: 1, 2, *Tetrataxis palæotrochus* (side and dorsal views); 3, *Climacammina cylindrica;* 4, *Ammobaculites stormi;* 5, *Bradyina magna;* 6, *Staffella keytei;* 7, *Wedekindellina euthysepta;* 8, *Triticites ventricosus.* Ostracoda: 9, *Healdia limacoidea;* 10, *Glyptopleura menardensis;* 11, 12, *Amphiscites centronotus* (end and side view); 13, *Hollinella kellettæ.* The insert at center top shows the specimens near natural size.

since they can be recovered from the drill cuttings and, when studied, serve to identify the formation through which the drill is passing. Because of their small size they are commonly spoken of as *micro-*

fossils (see Fig. 174), and their study has become a specialized science known as micropaleontology.

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Chapter 13

THE PERMIAN PERIOD, A CRISIS IN EARTH HISTORY

Momentous changes ushered the Paleozoic era to its close. As the mobile borderlands continued to rise and were thrust against the emerging continents, several of the great Paleozoic geosynclines were uplifted into fold mountains. These alpine chains stretched along the eastern and southern border of North America, crossed central Europe and southern Asia, and reached southward through the East Indian arc. The Urals also were formed at this time. As the enlarged continents interfered with the ocean currents, so these far-flung chains of lofty mountains disarranged the atmospheric circulation, and gave rise to climatic extremes of unprecedented severity.

The widespread glaciation and the long-continued aridity which swept over large parts of a world previously adjusted to warm, moist climates caused organic changes of the most drastic sort. Land animals, and land plants as well, struggling against a new and harsh environment, either made effective adaptations or became extinct. Judged by the changes that occurred, the Permian must be reckoned as one of the great crises in the history of life.

Founding of the Permian System. Almost as soon as the early Paleozoic systems were defined, Murchison and Sedgwick were concerned to know whether they would be recognizable in other regions. Travel in Germany, the Alps, and Belgium confirmed their hopes that they would. In all these regions, however, the rocks are much disturbed; hence, when rumors were brought back that Paleozoic strata were flat-lying over great areas in Russia, Murchison determined to extend his exploration in that direction. The publication of his great classic, *Siluria,* had brought him such renown that it was easily arranged for his expedition to proceed under the royal patronage of the Czar. He was joined in this undertaking by two friends, the Russian geologist, Count Keyserling, and his French colleague, De Verneuil.

In western England and Wales, where so many of the systems had been named, the Coal Measures are succeeded by redbeds that are in the main unfossiliferous. In Russia, however, Murchison found the Coal Measures overlain by a widely distributed series of highly fossil-

Fig. 175A (left). Early Permian (Wolfcampian) paleogeography. Symbols as in Fig. 154.

Fig. 175B (right). Early Middle Permian (Leonardian) paleogeography.

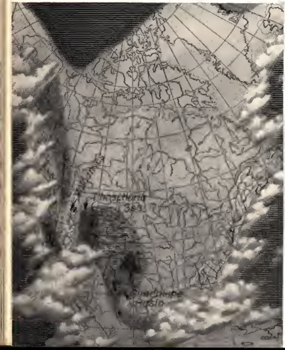


Fig. 175C (left). Late Middle Permian (Early Guadalupian) paleogeography. The horizontal line overprint marks areas of chiefly nonmarine redbeds.

iferous rocks, partly terrestrial but largely marine. These he first studied in the province of Perm on the western flank of the Urals, and from these exposures he called them the *Permian system.* Later work has shown that the system can be recognized in many other regions and that the older part of the redbeds overlying the Coal Measures of England and Germany is of the same age, though deposited under different conditions. The extensive development of Permian rocks in America was not recognized until after 1900, when the thick and richly fossiliferous sections of west Texas and New Mexico were discovered; but it is now clear that we have a Permian section unexcelled in any part of the world.

Physical History of a Changing World

Final Emergence of the Appalachian Geosyncline. Over eastern North America the change from Pennsylvanian to Permian conditions was transitional rather than abrupt. A mountainous borderland stretched from Newfoundland to Mexico, and the region of the Appalachian geosyncline remained a broad alluvial plain crossed by sediment-laden streams flowing westward toward the retreating sea. Deposition continued for a time across the central part of the geosyncline, as shown by the *Dunkard group* in southeastern Ohio and northwestern West Virginia (Fig. 175*A*). Probably these formations were originally more extensive along the trough and were largely destroyed by erosion later in the period.

Before Middle Permian time the uplift had become general over the whole of the eastern United States, so that the streams carried their burdens through to the basin which then occupied the Mid-Continent region, and deposition ceased over the Appalachian trough, which later in the period was folded into an anticlinorium and destroyed forever as a geosyncline. Thus with the close of the Paleozoic era came an end to one of the grandest features of ancient North America. Since earliest Cambrian time the Appalachian trough had subsided intermittently during every period, and had been the site of the most persistent interior seaways, trapping some 50,000 feet of strata. With the Permian came a change so profound that the region has never since been crossed by the sea!

The Dunkard group of Ohio and West Virginia is almost wholly nonmarine, including plant and insect fossils and a few thin coal beds. One thin zone has yielded, in addition, the brachiopod *Lingula* and a few shark spines, indicating that for a very brief time the sea reached


CARL O. DUNBAR.

Fig. 176. Guadalupe Mountains viewed from the south. The light-colored summit of the range is made of the Capitan reef-limestone, which in El Capitan Point (center) forms sheer cliffs over 1300 feet high. The slope below the limestone is formed of the Delaware Mountain sandstone which has a thickness of about 3000 feet.

this far eastward. Otherwise no marine Permian is known east of Kansas.

Vanishing of the Mid-Continent Seaway. The Mid-Continent region, from Kansas and Nebraska southward across Texas, remained a vast basin of deposition, as it had been in the previous period, and here, too, the change from Pennsylvanian to Permian conditions was transitional, though ultimately profound (Fig. 175).

Early in the period a shallow sea reached northward to southeastern Nebraska and eastern Kansas. In the extensive area of outcrops across Texas, Oklahoma, and Kansas, early Permian formations consist of alternating shales and thin limestones generally similar to those below. As we ascend in the section, however, evidence of a gradual and profound change is seen. In successive marine horizons the fossils are reduced to fewer and fewer kinds, as corals and echinoderms drop out and finally bryozoans and brachiopods also disappear. Above some hundreds of feet of such beds lies a thick gray shale (Wellington shale) bearing the great salt deposits of Kansas. It is succeeded in turn by red sandstones and maroon shales without fossils.

From this record we may infer the following history: At the beginning of the period an extensive epeiric sea occupied the region of the western Great Plains. It doubtless spread far east of the present outcrops and at one time reached temporarily to Ohio. Its outlet to the south across Oklahoma was restricted by the growth of a great delta from Llanoria, which surrounded the Arbuckle and Wichita mountains

as the modern delta of the Hwang-Ho surrounds the Shantung peninsula in China. Deltas were also growing eastward from the Colorado Mountains in New Mexico. The climate gradually became so arid that evaporation exceeded precipitation, and eventually a vast dead sea occupied the middle of the basin which centered over Kansas and Oklahoma. One group after another of the marine animals died out, and eventually the water became a brine from which salt was precipitated. Across Mexico and the Gulf a connection with the ocean was maintained through which more salt water was supplied as evaporation proceeded. Eventually the waters disappeared, either because the basin was filled to sealevel, or because of regional warping. Then, streams converging into the basin spread over its desert floor hundreds of feet of red mud and sands. For a time, extensive sand dunes covered parts of Oklahoma, where they are preserved in the Whitehorse sandstone. In the redbeds there are occasional zones of gypsum, which seem to indicate a temporary return of seawater and partial evaporation, though not enough to precipitate salt.

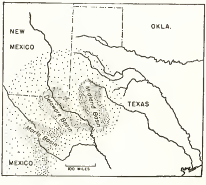


FIG. 177. Sketch map showing the extent of the Guadalupe basin (*sparse stippling*) and of its deeper subdivisions (*dense stippling*). After Philip B. King.

The *Kansas dead sea* marks the last stand of the Paleozoic epeiric seas east of the Cordilleran region. Even this sea had vanished before the close of the period, and we must turn to the far Southwest for a record of Late Permian time.

Guadalupe Basin of West Texas and New Mexico. The grandest Permian record in America, if not in the world, occurs in western Texas and southeastern New Mexico, where Permian strata total about 14,000 feet in thickness. This was a basin, occupied much of the time by a seaway which entered through Mexico, and toward which the drainage converged from the Eastern Interior. Out of the midst of it now rise the Guadalupe Mountains with a superb display of Permian rocks (Fig. 176), and for these the entire depression of Permian date may be called the *Guadalupe basin* (Fig. 177). Within this major depression there were three subsidiary and rapidly sinking areas, the *Delaware basin* in Trans-Pecos Texas and southeastern New

Mexico, the *Marfa basin* farther southwest, and the *Midland basin* of central-western Texas (Fig. 177).

As the rest of the Mid-Continent region emerged into lowland and the climate turned increasingly arid, local conditions in the Guadalupe basin gave rise to exceptional Permian deposition. Evaporation was matched by a steady flow of the marine water from the basin to its bordering shallow fringe. This caused deposition of limestone along the margins of the basins where the water was warmed and began to be concentrated. The result was the growth of reeflike limy banks between the deeper basins and vast marginal lagoons (Fig. 178). The

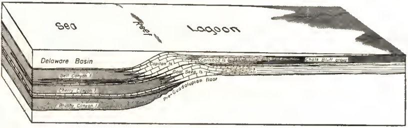


Fig. 178. Block diagram showing relations as they existed about the northern margin of the Delaware basin near the close of Middle Permian time. Front side of the block shows a section through the Capitan reef with deeper water in the basin at the left and shallow water in the lagoon behind the reef. Low delta plains appear at the extreme right. Length of the section along the front face about 12 miles; vertical scale exaggerated.

latter tended to become salt pans in which the red muds from the surrounding lands settled, to intertongue with deposits of gypsum and anhydrite and salt; while nearly pure limestone was accumulating over the reefy areas, and dark shales, dark limestone, and siltstone were deposited in the deeper water of the basins. In the lagoons, life was sparse or limited in variety; the reefs were inhabited by numerous highly specialized brachiopods and by other invertebrates which preferred this environment; and the sea floors of the basin included a varied and more normal population. Thus, in this region the Permian strata of any given time commonly present three distinct facies—one of lagoonal deposits (slabby limestone, gypsum, salt, and redbeds), one of massive reefy limestone, and another of normal marine strata—each grading locally into the other with astonishing abruptness (Fig. 178).

Finally, during the last epoch of the period, the marine water shrank into the deeper part of the basin to form a dead sea (Fig. 179), in which phenomenal deposits of salt and anhydrite were precipitated. These are discussed on page 292.

Changes in the Cordilleran Region. In the Far West, also, important changes were taking place. During early Permian time a southwestern embayment included eastern Nevada and much of Utah, and a new seaway ran northwestward across California. Thick and nearly pure limestones of this age in southern Nevada and in northern California imply that the near-by lands were still low. During the middle part of the period, however, volcanoes were active in California, western Nevada and Idaho, and eastern Oregon (Fig. 175*C*). This was apparently the first outbreak, and the forerunner of the great igneous activity that was to characterize the Pacific border during Mesozoic time. Near the middle of the period a new trough occupied the central part of British Columbia, extending southward into Washington and Oregon and bearing an oriental fauna not known farther south in America.

FIG. 179. Paleogeography of North America during latest Permian time (Ochoa epoch).

Permian rocks are also widely distributed in arctic America, notably along the west coast of Alaska, along the Yukon River, and in Cape Lisburne on the arctic coast of Alaska; also along the northern border of Sverdrup and Parry Island groups and in Ellesmere Island. These outcrops bear fossils indicating a common connection across the northern margin of the continent from Alaska to East Greenland and thence, via Spitzbergen and Novaya Zemlya, with the Ural region of the U.S.S.R.

Far-Reaching Orogeny and Continental Uplift

The Appalachian Revolution. During or at the close of this period Appalachia was thrust westward against the geosyncline, folding and thrusting the thick Paleozoic formations into a great mountain chain that extended unbroken from Newfoundland to Alabama. Practically all the structures now visible in the ridge and valley province

south of New England date from this disturbance. In New England and Maritime Canada the earlier disturbances (Taconian, Acadian, etc.) had more or less strongly deformed the rocks of the geosyncline, and there the effects of these several movements are compounded and difficult to separate; but south of New England the great mountain folds (Fig. 180) date entirely from the Appalachian revolution.

The movement was clearly later than the Early Permian, since the Dunkard group is gently deformed along with the older strata; and it was long before the middle of the Triassic, since the folds had been locally peneplaned before deposition of the Triassic Newark group began. In the absence of late Permian and early Triassic formations

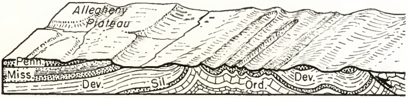


FIG. 180. Section across Appalachian structures in central Virginia, from the edge of edge of the Martic thrust appears at the extreme right, and two other thrusts are shown horizontal.

the movement can not be more precisely dated, though it probably culminated at the end of the Permian period.

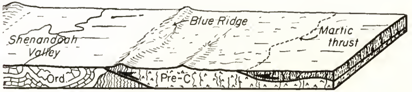
A cross-section of the Appalachian province (Fig. 180) shows clearly that the moving force was from the southeast. For example, along the eastern margin of the geosyncline a series of thrusts of great magnitude carried Cambrian and younger rocks westward until in places they rested upon the Coal Measures. Figure 181 shows the position of the greatest of these faults. The Martic thrust can be traced from Georgia to Pennsylvania, a distance of more than 500 miles, and the Blue Ridge fault extends over 700 miles, from Alabama into Pennsylvania. Westward movement of as much as 12 miles has been recorded on a single thrust.

In the belt of thrust faults the softer rocks are strongly crumpled (Fig. 182), and the folds are generally overturned to the northwest. The intensity of deformation dies out to the westward, however, and the folds are more and more open until the beds lie nearly horizontal in the Allegheny Plateau. The effect of the folding and faulting has been to reduce greatly the original width of the folded belt. It has been estimated that the section between Philadelphia and Altoona, Pennsylvania, was shortened by 100 miles,[1] and that the entire geo-

syncline, with an original width of 500 miles, is now reduced to 270 miles.

It is impossible to determine how high the mountains stood at any given time during the Permian, but they probably rivaled the modern Alps in grandeur. The amplitude of some of the folds in Pennsylvania (Fig. 183) would suggest a height of 5 miles, but this is probably too great, since the highest peaks must have suffered rapid erosion as they slowly rose; moreover, we do not know how much regional uplift went along with the folding.

Much igneous action accompanied the movement in the mobile zone. Extensive granites in the modern piedmont belt (Fig. 181) and prob-



the Allegheny Plateau (left) to the Piedmont slope near Richmond (right). The western to the left of it. Length of section about 100 miles; vertical scale about 2½ times the

ably part of the granites of New England were intruded at this time. Profound erosion has since removed such volcanics as may have existed, and laid bare these deep-seated intrusives. This removal of the younger rocks from the intruded masses has made it difficult to date the granites with assurance, but the fact that their minerals do not show strain or shearing proves that the intrusion did not precede the Permian thrusting.

The Ouachita Disturbance. The structures of the Ouachita Mountains of Arkansas and Oklahoma (Fig. 179) appear also to have been formed in the Permian. They present a northward-facing arc of intensely folded Paleozoic formations, lying in a series of great imbricated thrust sheets. The whole mass of the mountains has been thrust northwestward, probably tens of miles, over the eastern end of the older Arbuckle range. There is still some uncertainty as to the exact time of the thrusting. It involves thick Lower Pennsylvanian formations and is, of course, younger than these. Moreover, the Ouachita thrusts override the Arbuckle Mountain structures, which in turn were uplifted during Pennsylvanian time. It appears probable, therefore, that the Ouachita structures were formed by Permian thrusting.[2]

Volcanoes of the Pacific Border. In California the middle Permian (Nosoni) formation includes much volcanic tuff and lava. Recently a very characteristic Permian shark (*Helicoprion*) was found in west-central Nevada in tuffaceous shale interbedded in volcanics that exceed 13,000 feet in thickness. It is uncertain whether all the igneous material is Permian, but the middle part, at least, is so. Also in eastern Oregon and west-central Idaho volcanics (Castro formation) thousands of feet thick include a few thin marine beds bearing Permian fossils. These facts indicate the presence of an extensive field of volcanoes during the middle part of Permian time in eastern California, western Nevada, and along the Idaho-Oregon boundary. There was likewise much volcanic activity in central Mexico and Alaska in Permian time. This extensive outburst in the Permian was only the forerunner of the great igneous activity of the Mesozoic era.

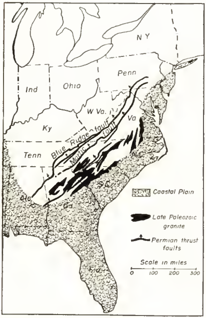


Fig. 181. Sketch map showing distribution of late Paleozoic batholiths (*solid black*) and the traces of major thrust faults (*heavy lines*) in the southern Appalachians. Overlapping deposits of the Coastal Plain are shaded. Adapted from Anna I. Jonas.

Permian Mountains of Eurasia. Crustal instability seems to have been as great in Europe as it was in North America during Pennsylvanian and Permian time. The Urals, which closely parallel the Appalachians in structure as in history, were folded during the Permian, while the Variscan chains were completed across southern England, Germany, and northern France.

Stratigraphy of the Permian System

Guadalupe Basin. In the Guadalupe basin, where the Permian strata reach a thickness of 14,000 feet, they have been subdivided as follows:

4. Ochoa series.
3. Guadalupe series.
2. Leonard series.
1. Wolfcamp series.

The *Wolfcamp series*, 500 to 700 feet thick, is entirely marine in this area and consists of interbedded limestone and shale. In the Glass Mountains, where it rests unconformably on the Marathon folds, it includes basal deposits of coarse limestone breccia. It is characterized by distinctive fossils of which the large ventricose foraminifer, *Pseudoschwagerina*, is most diagnostic. From numerous outcrops in extreme western Texas it dips eastward under younger rocks and reappears in north-central Texas (Fig. 175*A*). There it consists largely of shale but includes numerous persistent limestones and is divided into many formations and members (upper Cisco and Wichita groups). Traced

G. W. STOSE, U. S. GEOLOGICAL SURVEY.

Fig. 182. Folds in thin-bedded Silurian rocks, produced by the Appalachian revolution. The surface visible here is due to erosion and is not the original surface resulting from the folding. "Fluted rocks" on Great Cacapon River, West Virginia.

northward toward the Arbuckle Mountains, the limestones disappear and the entire series goes over into conglomeratic redbeds; still farther north, however, limestones reappear, and in Kansas and southern Nebraska, where these rocks have been called the Big Blue series, they are marine and richly fossiliferous. The change of character about the Oklahoma Mountains is due to the locally derived sediment and perhaps to the growth of a large delta deposited by streams draining the Eastern Interior.

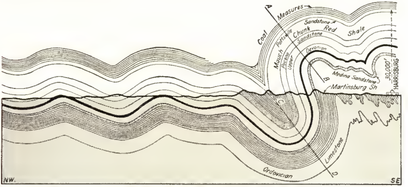


FIG. 183. Reconstruction of the eroded folds near Harrisburg, Pennsylvania, showing the size of the original folds. Length of section about 15 miles; vertical scale not exaggerated. *AB*, axial plane of an overturned anticline; *CD*, axial plane of an overturned syncline. Adapted from a diagram by George Ashley, Topographic and Geologic Survey of Pennsylvania.

The *Leonard series,* more than 2000 feet thick in the Guadalupe basin, varies locally from gray shale to nearly black shale to black limestone and to pure white limestone, but is wholly marine in this area. Dipping eastward under cover, it reappears in central Texas, in the form of redbeds with but few thin limestones and much interbedded gypsum. From here northward across Oklahoma and Kansas it is chiefly a redbed series. Fossil reptiles have been found in the red shales in Oklahoma, and both reptiles and labyrinthodonts (Fig. 193) in north-central Texas. These land animals were obviously living along the sluggish streams that wandered over a vast alluvial plain. Marine fossils are limited to a few very thin zones in Texas and Oklahoma, and apparently most of the redbeds are fluvial deposits. At the top of the series, however, there is a very widespread zone of gypsum (the Blaine formation) extending continuously from Kansas into Texas. It was apparently formed in vast lagoons largely cut off from the sea which still occupied the Guadalupe basin, and the pre-

cipitation of so much calcium sulphate implies severe aridity and excessive evaporation over the whole Mid-Continent region.

The *Guadalupe series* is most fully developed in the Delaware basin, where it is completely marine and shows with exceptional clarity the changes of facies discussed on p. 284. These are illustrated in Fig. 178. Around the margins of the basin, shallow banks of reeflike nature grew nearly to sealevel, forming a bar between the deeper water of the basin and the shallow lagoons that stretched away to the north and east. The Delaware Mountain group, formed in the basin, consists largely of sandstone and siltstone interbedded with numerous dark sandy limestone beds. It is still a problem how such a vast quantity of sand got through the lagoons and past the reefs into the depth of the basin; probably it was swept in through breaches in the reefs where streams entered from the Eastern Interior.

The reef limestone is peculiarly massive and now stands out in bold cliffs in the Guadalupe Mountains (Fig. 176). As the reefs rose some hundreds of feet above the floor of the basin and tended to grow basinward, the Capitan reef limestone here appears to overlie the Delaware Mountain sandstone, but in places along the flank of the range, beds of the dark limestone in the upper part of the Delaware Mountain group rise to intertongue with the white limestone, defining the original slope of the reef front. Back of the Capitan reef lie the lagoonal deposits, including bedded limestone near the reef, grading out into variegated shales and including precipitates such as gypsum and anhydrite. Over a vast area in central Texas, Oklahoma, and Kansas, red muds and sands accumulated to form the Whitehorse group, which may be largely nonmarine; but several thin beds of fossiliferous dolomite among the red shales in central Texas indicate temporary incursions of the sea over this low alluvial plain. At one time the marine waters reached to central Oklahoma, but in northern Oklahoma and southern Kansas part of the Whitehorse sandstone is cross-bedded in such fashion as to indicate dunes.

Meanwhile, dark marine shales and volcanics were accumulating in central and northern California, and thick deposits of volcanic material formed in eastern Oregon and western Idaho. In central Mexico (Las Delicias area) the marine Permian of this date likewise includes much volcanic material.

In British Columbia, on the contrary, the Permian formations (Cache Creek group) contain thick and rather pure limestones.

The *Ochoa series* (Fig. 184) reaches a thickness of 4450 feet in the Delaware basin and includes one of the world's greatest deposits of

salt. During the closing stages of the Permian the deeper parts of the Guadalupe basin formed a dead sea in the midst of a vast desert lowland (Fig. 179). Limited connection with the ocean via Mexico allowed an inflow of water to replace evaporation until saturation was reached and salt and anhydrite were precipitated. For a time the deposition was confined to the Delaware basin, and there the Castile deposits, as much as 2000 feet thick, consist almost wholly of chemical precipitates, chiefly banded anhydrite ($CaSO_4$) and halite ($NaCl$).

By the time this deposition was completed, the Delaware basin was largely filled, and deposition spread more widely over the Guadalupe

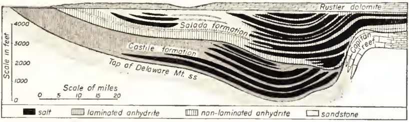


FIG. 184. Cross-section of the Delaware basin as it existed at the close of Permian time, showing the stratigraphic relations of the Ochoa series. Adapted from George A. Kroenlein.

basin. Concentration continued meanwhile, and the Salado formation accumulated to a maximum thickness of 2400 feet. Over much of the basin this formation is made up of rock salt or halite interbedded with anhydrite and including near its middle one of the greatest known deposits of potassium salts. Toward the margins of the basin the chemical precipitates grade laterally into variegated shales.

Following the chief salt deposition there were laid down the Rustler formation of dolomite and variegated shales, and, finally, the Dewey Lake redbeds of nonmarine origin.

The lamination so common in the Castile gypsum is well shown in Fig. 185. The light layers are nearly pure anhydrite, and the thin, dark layers have considerable organic matter and microscopic crystals of calcite. The well from which this core was taken passed through more than 1200 feet of such laminated material. Udden gave reasons to suspect that these are seasonal precipitates, the purer layers representing the drier season and the darker layers a more humid season. On this assumption, and from a count of the laminæ in this well core, Udden estimated that it required 306,000 years to deposit the Castile and Salado formations.

The total evaporation implied by so much salt is colossal. King has recently estimated that, if the salt were precipitated from normal seawater which constantly flowed into the basin to replenish the loss, an average evaporation of about 9½ feet per year over the 10,000 square miles of the basin would be required for a period of 300,000 years.[3] Since the average evaporation in Death Valley is only about 11½ feet, this is a striking commentary on the Late Permian climate of this region.

Yale Peabody Museum.

FIG. 185. Piece of a deep well core (natural size), showing the laminated anhydrite ($CaSO_4$) of the Castile formation. From Gresham Well No. 1 in Culbertson County, Texas. This is the well core on which Dr. Udden's study was based.

Cordilleran Region. As indicated in Fig. 175, the southern part of the Cordilleran trough was occupied by a shallow sea during much of Permian time. This left an imposing marine record in southern and eastern Nevada, most of Utah, southeastern Idaho, and extreme western Wyoming. Farther east, redbeds accumulated over a great area surrounding the Colorado Mountains.

Grand exposures of these Permian formations of the Far West are to be seen in the walls of the Grand Canyon (Fig. 186), where the lateral change of facies from redbeds to marine sediments may be studied. The general relations are suggested by Fig. 187. The Kaibab limestone is a key horizon rimming the inner gorge of the canyon in unscalable cliffs from 500 to 600 feet in height. It persists as a marine horizon from southern Nevada to northeast Utah, but in southeast and east-central Utah grades laterally into sandstone like the Coconino. The Toroweap formation (until recently

included in the Kaibab) consists of a marine limestone with redbed members both above and below it. The limestone thickens and largely replaces the redbeds in southern Nevada, but thins toward the east and is replaced first by redbeds and then by the massive, cliff-forming, light gray Coconino sandstone.

In the familiar Bass Trail section, in the eastern part of the Grand Canyon, the Coconino sandstone rests on soft red Hermit shale, and that in turn on the Supai formation of red sandstone, siltstone, and shale (Fig. 187). The Supai rests disconformably on the Redwall limestone of Mississippian age. Traced westward, the Hermit shale becomes sandy and takes on the character of the Supai formation.

CHARLES SCHUCHERT.

Fig. 186. Looking northwest from Yaki Point along the south wall of the Grand Canyon. Here the Permian formations total slightly over 2600 feet in thickness and rest disconformably on the Redwall (Mississippian) limestone.

At the same time the typical Supai redbeds become calcareous toward the west and grade over into the upper part of a great mass of marine limestone, which has been called the Callville formation just west of the Grand Canyon and the Bird Springs limestone still farther west. In southern Nevada that great mass of limestone, exceeding 5000 feet in thickness, includes in its lower part both Pennsylvanian and Mississippian deposits, while the upper part is Permian. The pre-Permian

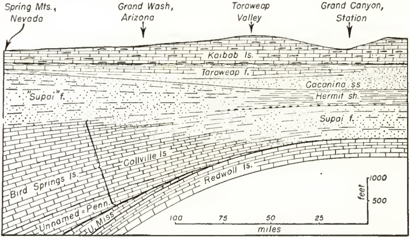


FIG. 187. Idealized section of the Permian formations between southern Nevada and north-central Arizona, showing the westward thickening and change of facies. The right end represents the well-known sequence at the east end of the Grand Canyon. Data from Edwin D. McKee (personal communication).

beds overlap out against the underlying Redwall limestone near the western end of the Grand Canyon, and the Permian part alone grades eastward into the Supai redbeds (Figs. 5, 187).

Throughout this province marine limestone, fluvial redbeds, and wind-blown sands were deposited simultaneously according to local conditions, and, as these conditions shifted geographically during the period, complex changes of facies occurred.

A great area of Mesozoic rocks separates the exposures of the Grand Canyon region from those of northern Utah and southeastern Idaho, where the Phosphoria formation is the most widely distributed and best-known Permian deposit. Where typically developed, it includes a basal member of black phosphatic shale and a thicker, upper member of cherty limestone, but toward the northeast it intertongues with, and is finally replaced by, red shales (lower part of the Chugwater

formation) that extend across Wyoming and into the rim of the Black Hills of South Dakota. Its marine fossils indicate that the Phosphoria formation is younger than the Kaibab. Its absence from the Grand Canyon region may be due to post-Permian erosion. The Phosphoria formation rests on Pennsylvanian or older beds in Wyoming, but in Idaho and northern Utah it is underlain by sandstones of great thickness (Oquirrh and Wells formations), the upper portion of which probably represents, at least in part, the Permian formations of the Grand Canyon section.

Climate

It was but a natural sequel to these and other great changes in the physical geography that climatic extremes were introduced. The extensive withdrawal of all the epeiric seas during Permian time removed one of the chief agents in stabilizing the temperature and providing moisture to the winds that crossed the interiors of the continents. The enlarged lands must have interfered greatly with the spread of warm ocean currents toward the poles, particularly in the southern hemisphere, where a land bridge (Gondwana) (p. 307) is believed to have crossed the Atlantic. At the same time each lofty mountain range which stood athwart a prevailing wind belt must have increased precipitation on the windward side and reduced it on the lee. The extensive highlands were chilled by their altitude. Under these conditions local extremes of climate are not the paradoxical but the natural thing.

Deserts. During the Permian period, deserts were probably more widespread than at any other time save the present. The dune sands and the widespread deposits of salt and gypsum in the central and western United States indicate a vast interior more arid than the present Great Basin. The salt beds that stretch from Kansas to New Mexico have been estimated to include 30,000 billion tons of salt and would require the evaporation of more than 22,000 cubic miles of sea-water with a salinity like that of the modern oceans. This precipitation, it must be remembered, occurred while only a part of the Permian formations were forming. The salt is not all of one age; in Kansas it is in early Permian strata, and in west Texas the chief deposits are in the latest Permian formations.

Central and western Europe were also strongly arid during a part of Permian time. In Soviet Russia the Uralian geosyncline was then a great trough lying just west of the modern Ural Mountains. For a

time shortly before the middle of the period it included a dead sea in the midst of a vast desert basin in which the Kungurian series formed. In the deepest part of this basin, about Solikamsk, these deposits exceed 4500 feet in thickness, are largely formed of salt and anhydrite, and include probably the world's largest accumulation of potash salts.

The Stassfurt region of Germany has another of the great deposits of salt, one which until recently has been the world's chief producer

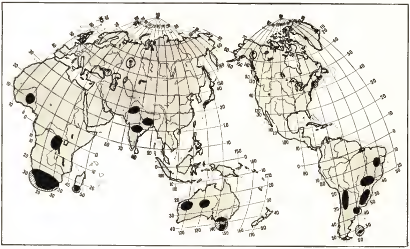


FIG. 188. Distribution of Permian glaciation (*black*). Base map by courtesy of the American Museum of Natural History.

of potassium. Thus three areas—one in southwestern United States, one in the U.S.S.R., and one in Germany—include the world's three greatest salt deposits, and all are of Permian date.

In South Africa the Permian deposits are largely nonmarine redbeds, though there they are not associated with salts or dune sand, and, on the contrary, include a wonderful assemblage of fossil reptiles.

Although aridity seems to have prevailed over much of the United States and central Europe, there was abundant rainfall in some regions, notably north China and eastern Australia, where important coal fields lie in the Permian rocks.

The Permian Ice Age. At times during the Permian period great areas in the southern continents were covered with ice sheets (Fig. 188). South Africa has the most spectacular evidence of glaciation, for there the ancient Dwyka tillite at the base of the Permian sequence includes large faceted boulders and rests upon the heavily scored and

polished floor over which the ice moved (Fig. 189). The ice cap covered practically all of southern Africa up to at least latitude 22° S. and also spread to Madagascar (which was then part of the continent). There were three or four centers of movement, but the greatest seems to have been in the Transvaal, which then was a plateau from which the ice moved southwestward for a distance of at least 700 miles. The tillite reaches a thickness of less than 100 feet in the northeast but increases to 2000 feet in southern Karroo. Australia was likewise the scene of extensive and repeated glaciations, the ice apparently moving northward across Tasmania, Victoria, and New South Wales. A series of five sheets of tillite is interbedded in some 2000 feet of Permian strata which have at least one horizon of commercial coal. South America bears evidence of glaciation in Argentina and southeastern Brazil, even within 10° of the equator. In the northern hemisphere, peninsular India, within 20° of the equator, was the chief scene of glaciation, with the ice flowing north; in the Salt Range on the southern flank of the Himalayas the thick Talchir tillite underlies the marine Permian.

A. P. COLEMAN.

Fig. 189. Glaciated floor beneath the Dwyka tillite near Kimberly, South Africa.

In the northern land masses other than India, on the other hand, evidences of glaciation are very restricted. The only certain evidence in North America is a small deposit near Boston, the Squantum tillite, which may be the result of a valley glacier from the rising Appalachians. Striated boulders in conglomerates have been found in the Permian beds in different places in Alaska, but the proof of their glacial origin is not conclusive. The same may be said of doubtful occurrences in England, Germany, south Russia, and central Africa.

It is almost certain that the Permian ice age, like the recent one of Pleistocene time, was a relatively brief episode in a long geologic period. The three widely spaced repetitions of glacial beds in the thick Australian sequence may indicate recurring glaciation in that continent. In any event, the main glacial deposits are in each region confined to a limited horizon of the older Permian rocks. The presence of large reptiles in the higher Permian redbeds of South Africa and of northern Russia would suggest a mild-temperate climate without freezing winters at the time when they lived.

The exact *time of the ice age* is difficult to prove in any of the glaciated regions. Possibly it was not the same in all the continents, though it would seem more probable that such extensive refrigeration must have affected the temperature of the whole world at once. It now appears that the best-dated glaciation occurred before the middle of the period, but long after the beginning of Permian time.

The most remarkable feature of the Permian glaciation is its *distribution.* It was chiefly in the southern land masses and in regions which now lie within 20° to 35° of the equator. This circumstance, more than any other, has made attractive the belief in "continental drift." If the southern continents were united to Antarctica until after Permian time, the glaciation may not have spread into low latitudes. A later "drift" of these continents toward the north would account, far more easily than any other means yet postulated, for the present distribution of the glacial deposits. But this premise itself is still in the realm of speculation!

Permian Life

Decline of the Carboniferous Floras. In the northern hemisphere the dominant types of Pennsylvanian plants lived on into Permian time. Lepidodendrons, sigillarias, calamites, cordaites, and seed ferns were the common forest types during the early part of the period. These swamp-dwelling plants were ill adapted to the oncoming aridity

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Fig. 190. A Permian landscape showing characteristic animals and plants. Part of a great mural by Rudolph Zallinger. Plants: 1, Cordaites; 2, Auricarioxylon, a conifer; 3, Lepidodendron, a scale tree; 4, Walchia, a conifer. Animals: 5, Varanosaurus, a reptile; 6, Eryops, an amphibian; 7, Edaphosaurus; 8, Dimetrodon; 9, Sphenacodon; 10, Aræoscelis. Numbers 7 to 10 are "fin-backs."

and to winter cold. With the passing of the period, therefore, hardier stocks with reduced foliage evolved, or came to the fore, as the Pennsylvanian types declined (Fig. 190). By the close of the period the great scale trees were almost extinct. The cordaites were likewise nearly gone, having first given rise to the conifers. Seed ferns were rare after the close of the period, and the race died out in the Jurassic.

True conifers rapidly sprang into the lead as the dominant type of woody trees, while primitive cycadeoids (allies of the sago palm) foreshadowed the expansion of higher plants in the Mesozoic.

The *Glossopteris* Flora of the Glaciated Regions. Throughout the southern hemisphere and in India, the Permian floras are charac-

terized by the small, hardy, thick-leaved "tongue ferns," *Glossopteris* and *Gangamopteris*. These had simple, tongue-shaped leaves borne on creeping stolons or rootstalks (Fig. 191). They bore seeds, and were not ferns but relatives of the cycads. Although they have been regarded as a response to the harsh climate of the glaciated regions, it has been commonly supposed that they did not actually live under frigid conditions but entered the glaciated regions during interglacial or postglacial ages.[4] Recent discovery of *Glossopteris* spores in the tillite in both India and Australia, however, indicates that *Glossopteris* actually lived under glacial conditions.[5]

By Middle Permian time some members of the flora had migrated as far as northern Russia and the Altai Mountains of Siberia, but none ever reached western Europe or North America. Along with the *Glossopteris* flora there lived in the southern hemisphere many ferns, conifers, calamites, etc., but none of the great scale trees. After the passing of the glacial climates, however, both *Lepidodendron* and *Sigillaria* succeeded in re-establishing themselves to a limited extent during the latter half of the period.

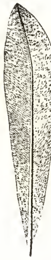

Fig. 191. Leaf of the Permian "tongue fern," *Glossopteris indica*. From Credner's *Elemente der Geologie*.

Insects. Insects (Fig. 192) were abundant and extremely varied at this time, though rarely preserved because of their delicate structure. However, a small locality near Elmo, Kansas, has yielded many thousands of specimens from a single thin bed in the Lower Permian, and other finds have been made in nearly equivalent beds in Oklahoma, in the Dunkard series in Ohio, in the Lower Permian of Russia, and in the Upper Permian of Australia. All these show great changes from the Pennsylvanian insect types. Although a few were still large in the Early Permian, the majority were small and many were minute, showing thereby a striking contrast with the giants of the previous age. Moreover, many new orders were now arising, foreshadowing the modern groups. Mayflies were common, true dragonflies were present, and in the Late Permian, beetles lived in Australia. Cockroaches persisted, but then, as ever afterward, played a minor role in the insect world.

Sprawling Reptiles and Labyrinthodonts. Even in the semiarid regions the old labyrinthodonts clung to the stream courses with sur-

prising success. Their heavily armored skulls are locally abundant in old stream-channel deposits in the redbeds of Texas and Oklahoma

Yale Peabody Museum.

Fig. 192. A primitive insect, *Dunbaria fasciipennis*, from the Early Permian beds near Elmo, Kansas, preserving the color pattern of the wings. About 2½ times natural size. Photograph not retouched.

and in the fluvial deposits of Germany and South Africa. Nearly all of them had broad heads, thick bodies, and short, feeble legs. As Huxley once said, they "pottered with much belly and little leg, like

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Fig. 193. A characteristic Permian labyrinthodont, *Eryops megalocephalus*. After a model by Dwight Franklin. Lower Permian of Texas. Length of this species, about 5 feet.

Falstaff in his old age" (Fig. 193). Probably none exceeded a length of 10 feet.

Reptiles increased greatly in variety during the Permian. The older

forms are known chiefly from the redbeds of Texas and Oklahoma, where conditions of preservation happened to be good, whereas the later kinds come from South Africa, India, northern Russia, and Brazil. Before the close of the period they had undoubtedly mastered all the lands, and some even reverted to aquatic life, both in the rivers and in the sea.

The great range of specialization which the Permian reptiles display (Fig. 194) emphasizes the rapidity of their evolution. Most of them

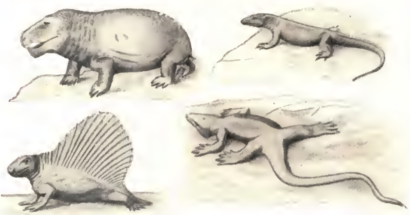

FIG. 194. Characteristic Permian reptiles. Lower right, *Limnoscelis*, from New Mexico; lower left, *Dimetrodon*, the fin-back lizard, from Texas; upper right, *Varanops*, from Texas; upper left, *Endothiodon*, from South Africa.

had long bodies, long tails, and short legs. While some were agile and lizard-like (*Varanops*), others were sluggish and semiaquatic like alligators (*Limnoscelis*), and yet others were thick-bodied and had stubby tails and short, thick legs. Many had sharp holding teeth and were certainly carnivorous; some had blunt teeth adapted to crushing shelled molluscs or crustaceans; and others, with toothless jaws like those of turtles, may have been herbivorous (*Endothiodon*). They had already deployed into several orders, but none of these corresponds to any of the living groups. Two features the Permian reptiles possessed in common: (1) none was very large, 8 or 10 feet being a maximum length; (2) all were four-legged creatures and most of them sprawled (Fig. 194).

The most bizarre of them all were the "fin-backs," so called because of their greatly extended neural spines. The reason for such extraordinary specialization is entirely problematical.

Far greater significance attaches to a group of stout-bodied flesh-eating reptiles known as *theriodonts,* which foreshadow the coming of the mammals. These are known chiefly from the middle Karroo formation (Upper Permian and Triassic) in South Africa. Unlike other reptiles, they had teeth differentiated into incisors, canines, and molars as do the mammals. Moreover, they carried their bodies off the ground instead of sprawling. Numerous details of skull and jaws confirm their ancestral relation to the mammals, though all of them were still reptiles (Fig. 207).

Specializations and Extinctions among the Marine Invertebrates. The marine invertebrates of the Permian evolved gradually out of the Pennsylvanian faunas. As some groups advanced steadily into progressive types, others assumed extravagant specializations which led shortly to their extinction; yet others, already on the decline, gradually died out.

The *cephalopods* (Pl. 11, figs. 5–9) showed the most significant gains, as goniatites with more and more complex sutures gave rise to typical ammonites. The rapid evolution of this group foreshadowed their spectacular rise to dominance among the marine invertebrates of the next era.

"The Permian was the Golden Age for the ammonids. Almost all the genera were branching out in various directions and almost anything (in the way of evolution) was possible for them. There is no forewarning, as yet, of the many tragedies of extinction, reversion, and degeneration that cloud the later history of this prolific group. . . . Thus the forebears of all the stately and beautiful genera of the Triassic may be seen in the simple and unpretentious forms of the Permian." [6]

Pelecypods and gastropods progressed steadily but more conservatively. Among the *brachiopods* (Pl. 12), which generally make up the bulk of the faunas, the productids remained the dominant group, while several new genera, growing fast to the bottom, developed into most extraordinary types, and some of them even grew conical shells mimicking corals (Pl. 12, fig. 11). Before the close of the period, however, all the productids and most of the other groups of brachiopods died out. The *fusulines* (Pl. 11, figs. 1–4) continued as important rock makers and attained their maximum size near the close of the period, though none survived the end of it. The trilobites, already nearly extinct, died out, as did all the honeycomb corals and the tetracorals; likewise most of the groups of crinoids, all the blastoids, and two of the orders of bryozoa.

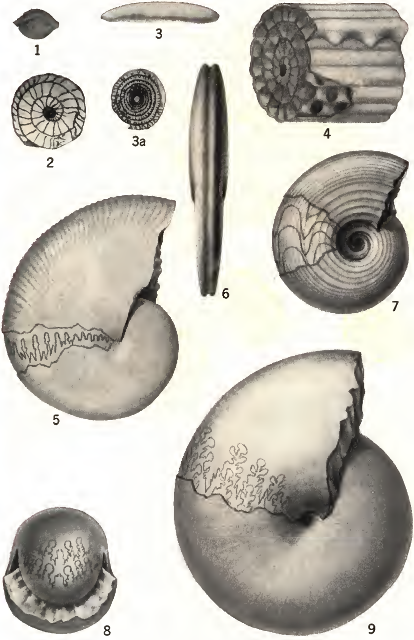

Plate 11. Permian Fusulinids (1–4), and Ammonites (5–9).

Fig. 1, *Pseudoschwagerina uddeni;* 2, enlarged section of same; 3, *Parafusulina wordensis;* 3a, enlarged section of same; 4, model of portion of a shell showing septa; 5, 6, *Medlicottia whitneyi* (lateral and edge views); 7, *Gastrioceras roadense;* 8, *Waagenoceras dieneri;* 9, *Perrinites vidriensis.* All natural size except 2 and 4. Drawn by L. S. Douglass.

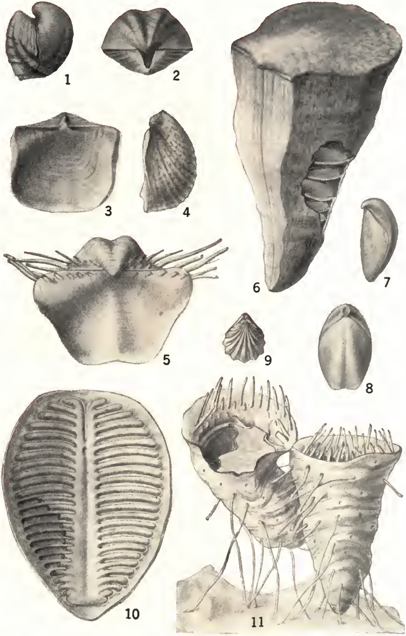

Plate 12. Permian Brachiopods.

Figs. 1, 2, *Parenteletes latesinuatus;* 3, 4, *Aulosteges medlicottianus;* 5, *Horridonia horrida;* 6, *Scacchinella gigantea* (with break in conical ventral valve showing internal septa); 7, 8, *Dielasma angulatum;* 9, *Hustedia meekana;* 10, *Leptodus americanus* (showing skeletonized dorsal valve and corresponding flanges in spoon-shaped ventral valve); 11, *Prorichthofenia permiana* (two specimens in position of growth, that at the left broken at the front margin to show the operculiform dorsal valve on its seat below the overarching spines; the dorsal valve also broken). All natural size. Drawn by L. S. Douglass.

Partly because of the great differences between the Late Paleozoic and Triassic life of the seas, and partly because in many regions (Germany and Russia especially) the Permian rocks have limited faunas, the misconception has arisen that the Permian was a time of great organic restriction and that the oceans may then have contained relatively few kinds of life. Such is, however, far from the truth. More species are now known from Permian than from Pennsylvanian rocks. The rich marine Permian faunas of the East Indies, especially on the island of Timor, contain not less than 600 species in 285 genera, and in the Salt Range (Punjab) of India there are 325 forms. Southwestern Texas has in its Permian rocks probably more than 500 species.

This was a time of rapid evolution, great specialization, and constant change. The net result was the disappearance of many of the characteristic groups of the Paleozoic life, but the change was orderly and gradual, not cataclysmic.

Gondwana Land Bridges

The living animals and plants of the island of Madagascar show so many resemblances to those of Africa that a former land connection is generally recognized. Similar faunal and floral evidence in some of the Paleozoic and Mesozoic formations of India, Africa, South America, and Antarctica strongly indicates that these lands also have been connected. A striking instance is the *Glossopteris* flora, which is characteristic of the Permian of the southern hemisphere and occurs with little change in each of the land masses mentioned above. Since these plants are entirely unknown in North America, they could have reached both Africa and South America only by some southern route. To explain such facts some geologists have invoked the theory of continental drift, believing that the continents were originally together and have since migrated apart; but most geologists now think it more probable that the continents have remained fixed, the former connections having been narrow land bridges such as that which now unites North and South America.[7]

On the assumption (now discredited) that South America, Africa, and peninsular India were once broadly connected to form a great transverse continent, this hypothetical land mass was called *Gondwanaland*. Those who believed in such a land assumed that the continents were eventually separated by a breakdown of the areas which now form the southern Atlantic and Indian oceans. This, however, involves the serious difficulty of explaining how such vast areas of

the crust could have increased in density until they settled to the level of ocean basins—a difficulty that is greatly lessened if we assume the connections to have been merely slender isthmuses or island arcs.

Land bridges between the southern continents appear to have existed from early Paleozoic time till the middle of the Mesozoic, and then to have begun to break down.

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IV. THE MESOZOIC WORLD

Chapter 14

THE TRIASSIC PERIOD

The Mesozoic Era. After the close of the Paleozoic era reptiles came into their own. Dinosaurs soon possessed the lands, while sea monsters splashed and slithered through the waves, and winged dragons took to the skies. Fourteen distinct orders of reptiles then thrived (there are but four in the modern world), and for more than a hundred million years they held undisputed sway, before their dynasty suddenly collapsed.

To the founders of geology who named this the Mesozoic era (Gr. *mesos,* middle, + *zoon,* life) this seemed to be the middle of the span of life on the Earth, but we now know that reckoning to be wrong. We have already passed in review far more than half of the history of the Earth and of life.

The Triassic Period. In Great Britain, where so many of the geologic systems were named, the Coal Measures are overlain by a thick sequence of redbeds. At first these were called the *New Red sandstone,* in contradistinction to the Old Red which lay below the Carboniferous. In Britain they form a lithologic unit, but in Germany a threefold division seemed natural because a gray marine formation (Muschelkalk) is present in the middle, separating the lower redbeds (Bunter) from the overlying nonmarine beds (Keuper and Rhætic). It was for this reason that the German geologist Alberti in 1834 gave the system the name *Trias* (L. *triad,* three).

Of course, such a threefold lithologic subdivision is not characteristic of the system generally, and modern usage would call for a geographic rather than a descriptive name, but Triassic is now so deeply intrenched that no useful purpose would be gained by trying to change it. This system represents the first period of the Mesozoic era.

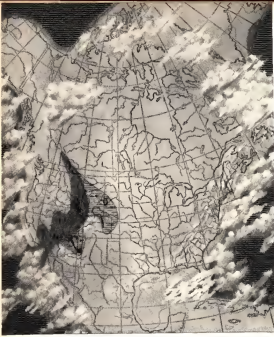

Fig. 195A (left). Early Triassic paleogeography. Nonmarine deposits, chiefly redbeds, are marked by horizontal black lines.

Fig. 195B (right). Middle Triassic paleogeography. Symbols as above.

Fig. 195C (left). Late Triassic paleogeography. Symbols as above. Outcrops (black) in the Appalachian region mark the Newark fault troughs.

Physical History of North America

Newark Fault Troughs of the East

After the Appalachian revolution the eastern half of North America, including the present continental shelf, was fully emergent for two long geologic periods. Erosion was in progress throughout the whole region during Early Triassic time, as the Appalachian Moun-

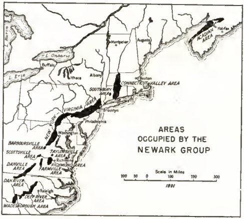

Fig. 196. Map showing the position of the chief areas occupied by the Newark group. After I. C. Russell, U. S. Geological Survey.

tains were being reduced and the debris transported beyond the present margins of the continent (Fig. 195). For the first half of the period there is no record save that of destruction of the older rocks by erosion. Then, as though the compressive stresses had relaxed, the axis of the Appalachian chain began to be riven by great normal faults that produced a narrow chain of block mountains bordered by downfaulted troughs (Fig. 196). The height and extent of the new block mountains are conjectural, but the structural troughs, which were filled as they sank, still retain a rich record of the time. The northernmost basin lies in Nova Scotia, and others are distributed southward into North Carolina, a distance of about 1000 miles (Fig. 195*C*). The Triassic strata formed in these troughs have been named the *Newark group* for the exposures near Newark, New Jersey, where they probably exceed 20,000 feet in thickness; and the structural troughs are known as the Newark basins.

The Connecticut Trough as a Type. The Triassic trough of central Connecticut stands near the middle of this chain of basins and will serve well for further description. It extends northward from New Haven across Connecticut and most of Massachusetts, its length being nearly 100 miles and its greatest breadth about 25 miles.

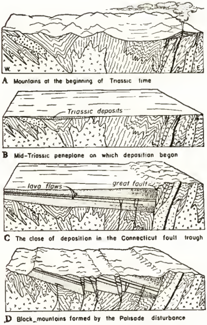

FIG. 197. Four stages in the development of the Triassic basin of central Connecticut. View northward. Length of sections, about 30 miles. Modified from J. Barrell.

Block *A* shows the complex structure and rugged topography inherited from the Appalachian revolution; block *B* shows the beginning of Newark deposition after the region was largely peneplaned; block *C* shows the Newark fault trough fully developed through subsidence along the great fault; block *D* shows the final stage with the Newark deposits complexly faulted during the Palisade disturbance. The modern structure of the region dates from this time. Triassic strata stippled.

The Triassic beds dip eastward at angles of 15° to 30° against a great fault that bounds the basin on the east and must have a maximum throw of about 3 miles (Fig. 197).

The Triassic rocks of the basin are conglomerates, sandstones, siltstones, and shales, with interbedded flows of dark (basic) lava. Perhaps half of the sediments are gray, but the most prominently exposed beds are red, and these commonly give the impression that the whole group consists of redbeds.

The sediments are poorly sorted and irregularly bedded, sandstones grading laterally into siltstones or conglomerate. All the coarse deposits are arkosic, and much of the feldspar is remarkably fresh. The conglomerates are thickest and coarsest along the eastern margin of the basin and clearly represent fans built where torrential streams debouched from the highlands to the east. In Connecticut the Newark group has an estimated thickness of 10,000 to 13,000 feet, and in New Jersey it may reach more than 20,000 feet, but it diminishes to 2000 or 3000 feet in the southern basins.

The associated igneous rocks take the form of flows, sills, and dikes. They are mostly dark and fine-grained and are commonly identified as trap, but the larger sills have the texture of *dolerite*. The largest of these igneous bodies are flow sheets, three in number, which lie in the middle part of the series, each separated from the next by several hundred feet of sedimentary beds (Fig. 197*C*). The middle one of these reaches a thickness of about 500 feet and forms conspicuous ridges, such as the Hanging Hills of Meriden and Saltonstall Ridge. That each of these was a surface flow is clearly shown by the facts that (1) its upper surface is coarsely amygdaloidal and (2) the overlying sedimentary beds contain fragments of the scoriaceous lava but show no effect of heat as does the floor under the lava. These flows were remarkably free of explosive violence, for ash and bombs are known in only one small area near the Holyoke Range in Massachusetts. The lava must have been very fluid to spread in such flat and extensive sheets. Great numbers of dikes cut the underlying strata.

The middle third of the Newark group, associated with the lava flows, is generally finer-grained than the lower and upper part, and is predominantly dark gray in color, whereas the higher and lower beds are chiefly red.

No marine fossils have been found anywhere in the Newark group, but land plants and fresh-water fishes are locally abundant in the darker gray beds, and dinosaur tracks in the redbeds are more plentiful than anywhere else in the world. Ripple marks are common, and mud cracks cover many of the bedding planes. The imprints of Triassic raindrops are in many places associated with the footprints and mud cracks (Fig. 198).

With these facts in mind, it is not difficult to reconstruct the events that transpired here during the latter part of Triassic time (Fig. 197). The Connecticut basin was then a fault trough similar to the California trough which now lies between the Coast Ranges and the Sierra Nevada. A range of block mountains bordered it on the east, with a fault scarp facing the basin. Repeated movement along the great fault depressed the basin and elevated the mountains. Meanwhile the streams which reached the basin from the uplands dropped most of their sediment here, building fans along the eastern border and fluvial deposits over the floor of the basin. Before the igneous activity began, the basin was well drained by through-flowing streams, and much of the mud was carried away, while gravel, sand, and silt were dropped.

The uplands must have had plentiful rainfall to develop such a quantity of red mantle as is represented in these sediments, but the rains were probably seasonal. Thus the mud that spread over the floodplains during wet seasons lay exposed to the sun during the dry months. Dinosaurs crossed and recrossed, leaving their tracks in the mud. The last spatter of passing showers also left imprints of raindrops where the mud was exposed and still soft. During the dry sea-

Yale Peabody Museum.

FIG. 198. Slab of Triassic sandstone from Turners Falls, Massachusetts, showing imprints of raindrops and tracks of two dinosaurs. The larger tracks were made before the last rainfall; the smaller ones afterward.

son the mud shrank and developed mud cracks and then was sunbaked and hardened, so that it could hold these surface features until they were buried by a new layer of sediment and preserved.

Where the drainage was good and the ground water not close to the surface, the iron-stained sediments remained red. After the first lava flow, however, the drainage was imponded, and for a considerable time swampy conditions obtained over much of the lowland; during that time vegetation accumulated with the sediments and in its decay reduced the iron oxide, producing gray or dark colors. Such conditions held until after the last flow, and then, with better drainage, redbeds again accumulated over the basin.

Other Newark Basins. The geology of the other Triassic fault troughs is, in general, like that sketched above. In the Acadian area

the sediments are predominantly red, and there is a large trap sheet, but apparently only one. The dip here is northwest, and the bounding fault is on the west side (Fig. 196). In the New York-Virginia and Danville areas also the dip is westward, whereas in the Deep River and Wadesboro areas it is to the east. As we follow the basins southward from Connecticut, an important change is seen in the character of the sediments, since more and more of the sandstones and shales are greenish-gray instead of red. Finally, in the Danville area, there are interbedded coals which locally reach a thickness of 26 feet. This

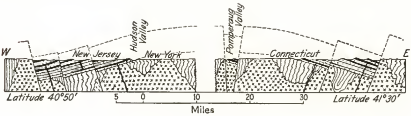

FIG. 199. Idealized section suggesting the probable structural relations of the Triassic basin of Connecticut and that of Pennsylvania and New Jersey. The western part of the section follows the line of latitude 40° 50′ and is about 50 miles south of the line of the section in Connecticut. Moreover, a section about 35 miles long is omitted in the center. In Connecticut the Triassic strata dip eastward toward a great fault, and in New Jersey and Pennsylvania they dip westward against another great fault. As here interpreted, these basins were on opposite sides of a great low arch. It is not certain that the Triassic sediments ever extended entirely across the arch. Triassic sandstone, dotted; trap rock, black; old metamorphic rocks, wavy lines or crosses. After C. R. Longwell.

may imply that the rainfall was more evenly distributed through the year in the southern basins, or that it was greater, or that the basins were not so well drained.

In the New York-New Jersey area, as in Connecticut, there are three great flows which may indicate equivalent periods of eruption in the two troughs (Fig. 199). Likewise there is a thick sill near the base of the group whose eroded margin now forms the Palisades of the Hudson River from New York City northward for a distance of nearly 50 miles. A few great dikes which cut across the margins of the area and extend out into the older rocks of the piedmont in southeastern Pennsylvania and central Maryland suggest that the volcanic activity was not confined to the structural troughs, but for the most part the Triassic volcanics are preserved only in the basins whose subsidence protected them from later erosion.

Age of the Newark Group. The fishes and plants of the Newark beds indicate that the entire group belongs to the later half of Triassic

time. In other words, at least half a period had elapsed after the folding of the Appalachians before the Newark basins began to form, and to trap sediments. Herein lies the explanation of the remarkable unconformity at the base of the Triassic. Wherever the basal contact has been seen, the Newark beds rest upon a surface of slight relief which cuts across the complex structures of the Paleozoic and older rocks. In Nova Scotia truncated folds of Pennsylvanian and older strata are overlain by the Triassic. In eastern Pennsylvania the strongly crumpled Ordovician limestones are in contact with the gently tilted redbeds in places where all the later Paleozoic rocks had been removed before the beginning of Newark deposition. In short, the Appalachian folds had been worn down and the region at least partially peneplaned during the late Permian and the earlier half of the Triassic.

The Arid Cordilleran Basin

Triassic rocks are widely distributed through the Rocky Mountain region from Idaho and Wyoming southward across Utah, Colorado, Arizona, New Mexico, and western Texas. This is the greatest area of continental Triassic deposits in North America. Here continental redbeds predominate, though marine members of the older Triassic interfinger from the west. Bright red or maroon shales and cross-bedded red sandstones make colorful landscapes like the "Painted Desert" of Arizona and the "Great Red Valley" in the rim of the Black Hills.

The maximum thickness of these redbeds is found in the western part of the region, where, in southwestern Utah and northwestern Arizona, it amounts to 3000 to 4000 feet (see Fig. 200), and in general the system thins out to several hundred feet toward the east in Colorado and Wyoming. Beds of gypsum occur at various horizons in the red shales, especially in the eastern and northeastern parts of the region. There is also considerable volcanic ash in the redbeds of Arizona and Utah. Much of the detrital sediment came from the old crystalline uplifts of the Colorado Mountains in Colorado and northern New Mexico, for the Triassic formations become coarser-grained toward regions like the Uncompahgre Plateau (western Colorado), where they overlap against the ancient granites.

Throughout the Colorado Plateau a twofold division is generally recognizable. The lower portion, known as the *Moenkopi* (*mō′·ĕn-kō·pē*), is generally a soft formation of sandy shale and siltstone with local thin beds of salt and thicker ones of gypsum; it is mostly water-laid and rather evenly bedded. It grades westward into defi-

UNION PACIFIC SYSTEM.

Fig. 200. West Temple of the Virgin, Zion National Park, Utah. A 4000-foot wall of Triassic and Jurassic rocks carved out of the Colorado Plateau by the Rio Virgin. Triassic rocks extend up to the base of the Navajo sandstone. The ranch houses at the bottom indicate the scale. For regional relations, see Fig. 267, p. 416.

nitely marine beds and finally into limestones in Nevada, but toward the east becomes a bright red shale and includes much sand. In western Arizona it is a variegated formation with interbedded red and gray shales and siltstones.

The upper series, known as the *Chinle* (*chĭn·lee′*), is more sandy and generally more brilliantly colored, varying from white through reds, yellows, and blues. It rests with an erosional unconformity on the Moenkopi over the eastern part of the plateau region, and there has a striking basal conglomerate, the *Shinarump* (*shĭ·nă′·rump*) (Fig. 200).

Fossils are extremely rare throughout the redbeds. With the exception of those found in certain thin marine members that finger into the Moenkopi from the west, the only known fossils are remains or tracks of terrestrial or fresh-water animals, and petrified wood. River clams occur here and there, and at certain horizons there are "bone beds"

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Fig. 201. Chinle formation showing variegated color and abundance of fossil wood. Petrified Forest National Monument, Arizona.

of vertebrate remains. These were partly labyrinthodonts (amphibia), but mainly reptiles of crocodile-like form and habits (phytosaurs), all of which inhabited the stream channels of the time. Petrified wood is abundant locally in the Chinle sands, as at Petrified Forest, Arizona (Fig. 201). The fossils, like the physical features of the rocks, therefore indicate that the redbeds were for the most part, at least, deposited above sealevel. The gypsum that is so conspicuous in Wyoming may, however, represent evaporation in lagoons where the marine waters spread temporarily eastward from Idaho and Nevada. The Moenkopi was deposited over a vast low alluvial plain sloping westward from the Colorado Mountains to the margin of a shallow epeiric sea, whose shore fluctuated back and forth over the western part of Arizona and Utah. The Chinle was more completely independent of the sea and was spread by sluggish streams over a broad semiarid basin with seasonal rainfall; locally there were swamps and shallow lakes, whereas the higher ground surrounding the basins had scattered stands of conifers. In the western lands there were explosive volcanoes, shedding ash far about.

The Californian Sea and the Marine Trias of the West

During Triassic time the Pacific Coast geosyncline appeared inside the margin of the continent, its axis running parallel to the present

Pacific Coast from California to Alaska. It was not, however, so extensive in early Triassic time as it was from the middle of the period until well into the Cretaceous, when it was one of the major features of the continent and was repeatedly flooded by marine waters. It appears to have been separated from time to time into two embayments by a positive area in the latitude of Oregon and Washington. In this event, it is convenient to distinguish the *Californian Sea* in the United States and the *Columbian Sea* in British Columbia and Alaska. West of the geosyncline lay island borderlands of unknown extent (Fig. 195).

In California, Triassic formations, nearly all of marine origin, attain a thickness of 4000 feet or more and present a sequence of deposits and faunas that compare favorably with those in most parts of the world. The greatest known section, however, is in south-central Nevada, where Triassic formations exceed 25,000 feet in thickness. Here the Lower Triassic, some 3000 feet thick, consists of shales and sandstone; the Middle Triassic, about 12,000 feet thick, contains mostly volcanics with a small percentage of interbedded sediments; and the Upper Triassic, more than 10,000 feet thick, is made up chiefly of limestone and limy shale, with minor amounts of interbedded volcanics.

In California and British Columbia the post-Triassic disturbances have so deformed these rocks that their areal relations are not well known.

During early Triassic time the marine waters spread eastward from the Californian trough across Nevada and southern Idaho, where limestones and gray shales with abundant ammonites interfinger with the redbeds of the Cordilleran basin. An arm of this sea extended far north into Canada along the borderline between Alberta and British Columbia (Fig. 195*A*). Shallow arms of it may have spread temporarily as far east as the Black Hills of South Dakota to form the gypsum of the red Spearfish shales. However, no marine fossils are known east of western Wyoming.

During middle and late Triassic time marine water was restricted more definitely to the Pacific Coast geosyncline and did not spread east of Nevada (Fig. 195*B, C*).

The Columbian Sea made its appearance in middle Triassic time, and it seems to have been studded with active volcanoes throughout the later part of the period. In the region of Vancouver Island and the Queen Charlotte Islands the Upper Triassic alone has a thickness of 13,000 feet, but of this more than nine-tenths consists of submarine eruptives—lava flows, volcanic breccia, and tuffs. With these are

interbedded zones of shale and quartzite having marine fossils. The sedimentary rocks are generally thin or lacking in the eastern part of the geosyncline but thicken westward, one such formation on Vancouver Island having a thickness of 2500 feet.

Other volcanics of great thickness in western Nevada, northeastern Oregon, and west-central Idaho, originally thought to be Triassic, are now known to be largely Permian (see p. 285).

In Alaska, the Triassic is represented by thick formations of limestone capped by an extensive black shale.

Palisade Disturbance and the Close of the Period

In the Appalachian region, faulting occurred repeatedly along a few great rifts, but the Newark group, with its interbedded lavas, accumulated with no more disturbance than a very slight eastward tilt due to the unequal depression of the floor.

At the close of the period, however, general uplift began, accompanied by complex normal faulting that tilted the Triassic beds more steeply and broke them into innumerable fault blocks as suggested in Fig. 197*D*. Subsequent erosion has beveled these tilted blocks and etched out the resistant trap sheets into the prominent ridges of today, such as the Palisades of New York, the Hanging Hills of Meriden in Connecticut, and the Holyoke Range in Massachusetts. All the structures involved, however, date from the faulting at the close of the Triassic, an orogeny known as the *Palisade disturbance.* The regional uplift that accompanied the faulting brought an end to deposition in eastern North America until after Jurassic time.

It is worthy of note that, although the Palisade disturbance followed the axis of the Appalachian system, the forces involved, as well as the structures produced, were almost the antithesis of those of the earlier deformation. The forces of horizontal compression that made the Appalachians had apparently relaxed, to give way to normal faulting and broad uplift.

In the western part of the continent, it is inferred that there was general emergence, since latest Triassic and most of early Jurassic time are not represented there, but no pronounced disturbance is known.

Triassic History of Other Countries

In a general view of the Earth, one of the most remarkable features of the Triassic is the almost universally emergent condition of the continents, and the extensive spread of nonmarine deposits, largely redbeds.

In *South Africa*, nonmarine formations of great thickness (upper Karroo) are overlain by volcanics and shot through with basic intrusions of extraordinary magnitude (Drakensberg volcanics). The lower part of the series includes gray sandstones, siltstones, and shales with thin beds of coal and abundant plant remains, but the middle part consists of thick redbeds with mud cracks and a very interesting reptilian fauna. Overlying the redbeds come purer, wind-blown sands varying in thickness up to 800 feet. The succession of formations is interpreted to imply a growing aridity that resulted in desert conditions over a considerable area in South Africa before the close of the Triassic.[1] The basic igneous rocks intruded into this series have a present area of fully 220,000 square miles, and, before their erosion, covered at least 330,000 square miles in a great belt between latitudes 26° and 33° S. that extended from the east coast probably to the Atlantic. With a volume estimated as between 50,000 and 100,000 cubic miles, this constitutes one of the greatest known masses of basic intrusives. The time of its intrusion is either late Triassic or more probably early Jurassic.

The Permian basin west of the Urals in the U.S.S.R. also includes a vast area of redbeds (upper part of the Tatarian series) that have yielded striking vertebrate fossils.

In the Paraná basin of southern *Brazil*, late Triassic redbeds with reptiles similar to those of Africa are also overlain by enormous lava flows which still cover an area of some 300,000 square miles to a depth ranging from 400 to 2000 feet.[2] These lavas, like those of South Africa, may be dated as either late Triassic or early Jurassic.

In *England*, *Germany*, and *France*, the Triassic is represented chiefly by redbeds of nonmarine origin. In France these are salt-bearing, and those in Germany have gypsum. On the other hand, southern Europe was covered by a vast epeiric sea in the Tethyan geosyncline, which continued eastward through the Himalayan region and thence southward into the East Indian arc. Throughout this vast area, there is a fine development of marine Triassic, which is nowhere better displayed than in the dolomite peaks of the Tyrolean Alps. The dolomites of the South Tyrol are in places over 3000 feet thick and were almost wholly built by marine reef-making algæ.

Climate

We have noted the evidence of widespread aridity in North America, South America, South Africa, and western Europe. On the whole,

arid or semiarid climate seems to have been remarkably widespread during the Triassic. Perhaps this was partly due to the size of the emergent land masses, since the interiors of the continents, dependent for their moisture upon evaporation from the seas, include the chief deserts of the world. At the same time, parts of the Triassic lands were well watered, just as parts of the present continents are humid.

In view of the widespread Permian glaciation, it is noteworthy that no glacial deposits have been found in the Triassic rocks.* The temperature had become mild long before the close of the Permian in places where glaciers had existed before. This we may infer from the distribution of late Permian and Triassic vertebrates, all of which were cold-blooded, that is, without a device to keep their bodily warmth above that of their environment. Modern reptiles and amphibia, without exception, become torpid and helpless when the temperature drops to near freezing. Small species may take refuge in holes and hibernate, but all large species are confined to regions without frost. For example, the alligators and crocodiles, the great land tortoises, the large lizards and boas, all live in the tropics or subtropics. It is therefore highly probable that the dinosaurs as well as the sprawling reptiles and the large labyrinthodonts of the Triassic could not endure freezing weather. Before the close of the period, corals had re-established themselves and were making small reefs in the seaways along the Pacific coast of America as far north as Alaska. However, since these are of few kinds and the reefs are small, it is probably not safe to infer that the water was subtropical so far north.

Life of Triassic Time

Land Plants. The plants of this time are still imperfectly known, for less than 400 species have been described from all the world, and these are chiefly from the Upper Triassic formations. This situation may be due to an actual impoverishment of plant life because of the harsh climates, but it more probably results from the fact that redbeds are a poor environment for the preservation of plants.

In America we get two glimpses of the Triassic flora, one in the foliage preserved in the dark shales of the Newark group, particularly

* Triassic or Jura-Triassic tillites are reported in equatorial Africa west of Lake Tanganyika. The tillites occur in the Lubilache formation. Valves of *Estheria* occur. It is not proved that this formation is of Triassic age, and it may after all be of Permian time. See Coleman, *Ice Ages,* 1926, p. 86.

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Fig. 202. Petrified logs in Petrified Forest National Monument, Arizona. This is near the base of the Chinle formation.

in the southern areas (Virginia and the Carolinas), the other in the petrified logs of the western redbeds, as at Petrified Forest, Arizona.

The first is a swamp flora of ferns and scouring rushes, to which are added, where streams entered the swamps, the transported leaves of conifers and cycads that formed the forests on the uplands and slopes.

The Petrified Forest of Arizona, on the contrary, has yielded chiefly petrified logs, although foliage has been found in several places,[3] recording cycadeoids and ferns that grew along the stream courses. The logs are of conifers, not unlike the great pines that now stand in stately grandeur upon the rim of the Colorado Plateau. Many of the logs are of noble size, some attaining a diameter of 10 feet at the base and a length exceeding 100 feet. It has been estimated that some of

these trees stood nearly 200 feet high (Fig. 202). They now lie imbedded in the Chinle shale, petrified as agate.

These two occurrences give a fair representation of what we know of Triassic land plants of the world as a whole. The forests were then

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FIG. 203. Glimpse into a Triassic landscape with characteristic plants and animals. Part of a great mural by Rudolph Zallinger.

Plants: 1, a broadleafed fern, *Macrotæniopteris;* 2, a primitive cycadeoid, *Wielandiella;* 3, a long-stemmed cycadeoid, *Palæocycas;* 4, a conifer, *Voltzia.* Animals: 5, a primitive reptile ancestral to the dinosaurs, *Saltoposuchus;* 6, one of the smallest of dinosaurs, *Podokesaurus* (length about 3 feet); 7, one of the largest of Triassic dinosaurs, *Plateosaurus,* a probable ancestor of the great sauropods of the next period (length about 20 feet); 8, a mammal-like reptile, *Cynognathus.*

predominantly of conifers much like our modern evergreens, and of cycads (Fig. 203). The undergrowth consisted of ferns, tree ferns, and scouring rushes. The chief groups of Paleozoic plants were extinct, or nearly so. The seed ferns, so characteristic of the Coal Measures, had largely vanished, and the great scale trees are known only from rare specimens of *Sigillaria* in the early Triassic and a few other doubtful representatives. *Lepidodendron* is not represented, and cordaites were no longer conspicuous.

FIG. 204. A Triassic phytosaur, *Rutiodon*. Plants in the foreground are rushes, and the tree in the background is a cycad. After S. W. Williston. The phytosaur had a length of 10–12 feet.

Land Animals: The Beginning of a Reptilian Dynasty. The vertebrates of the lands were now varied and evolving rapidly. While the labyrinthodonts attained their culmination in size and variety, they were already far surpassed by the *reptiles*, which showed themselves adapted to all conditions of life on the lands, and early in the period began to invade the seas and compete with the fishes as do the modern seals and whales. Phytosaurs were common in the streams, and several other orders of reptiles, now extinct, were adapted to life on the lands. The phytosaurs resembled the modern gavials in appearance and habits but were not closely related to crocodiles. Their bones are found in association with river clams and lungfishes. One species from western Texas had a length of 25 feet. All the phytosaurs were confined to the Triassic period (Fig. 204).

Fig. 205. A Triassic dinosaur, Anchisaurus colurus, after a model by R. S. Lull, based on a skeleton in Yale Peabody Museum. The animal was about 6 feet long.

Dinosaurs (Gr. *deinos,* terrible, + *sauros,* reptile) made their appearance in the Triassic and by the middle of the period outnumbered all other kinds of reptiles and held complete sway over the lands—a dominion they were destined to hold until the close of the Mesozoic era. Unlike other reptiles, they were adapted to a running locomotion, carrying their bodies up off the ground like mammals, with the legs under the body, not at its sides. Other reptiles sprawl. This is the only obvious feature that ties the diverse types of dinosaurs together as a natural group, for they vary by the widest extremes in size, bodily form, and habits. Indeed, they constitute, as we now know, not a single great order of reptiles but two that are only remotely related, having had very different origins.

Compared with the giants of later Mesozoic ages, the Triassic dinosaurs were hardly "terrible reptiles," for nearly all of them were slender of build and few reached a length of more than 10 or 15 feet. Almost all the known Triassic species were bipedal (Fig. 203) and shaped somewhat like a kangaroo, with powerful hind legs and a thick, powerful tail which aided in balancing the body as they ran. The bipedal dinosaurs did not leap like a kangaroo, however, but ran like an ostrich. The nature of their abundant tracks makes that quite certain.

The side toes on the hind feet were already vestigial in most of the Triassic species, so that they made three-toed footprints that were for a long time mistaken for bird tracks. Although the dinosaurs were very numerous in the eastern United States, skeletal remains are extremely rare, because the redbeds were a poor environment for the preservation of bones. As the dinosaurs crossed and recrossed the mud flats of the Connecticut trough, however, they left an amazing record, not of dead but of living creatures, now hurrying in search of food or water and again stopping to rest and to leave in the soft mud an impression of the body and the tiny front feet. The best-known American form is *Anchisaurus* (Fig. 205), a slender, graceful animal that reached a length, over all, of probably 5 to 8 feet; its birdlike tracks have a length of 3 or 4 inches. Some of the similar tracks 5 or 6 inches long indicate larger species. The largest track of all (*Otozoum*) is that of a ponderous type, probably larger than an elephant, for its foot was more than 18 inches long and almost half as broad.

In 1947 a rich deposit of small Triassic dinosaur skeletons was discovered near Abiquiu, New Mexico.[4] Dinosaurs similar to those of America were also present in Europe, and nearly complete articulated skeletons of carnivorous dinosaurs were discovered in the Upper Triassic of China in 1947.[5]

South Africa had, besides the dinosaurs, several other orders of primitive reptiles, some of which were squatty and heavy of build. More interesting than all other reptiles of the time were the theriodonts, a group from which the primitive mammals evolved during the Triassic. Some of these, like *Cynognathus* (Fig. 206), form the closest

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Fig. 206. A mammal-like reptile, Cynognathus, from the Triassic beds of South Africa. A painting by F. L. Jaques, made under the direction of W. K. Gregory.

approach to true mammals in every detail of the skeleton. The teeth, for example, are differentiated and the dentary bone forms nearly the entire lower jaw. This group of mammal-like reptiles is known in America from only two tiny jaws, each about the size of that of a rat (Fig. 207). These were found in one of the Triassic coal mines in North Carolina, and were for many years supposed to belong to true mammals.

Teeth and jaws occurring sparsely in the late Triassic (Rhætic) beds of Germany resemble those of a primitive group of mammals known as *Multituberculata* (p. 464 and Fig. 298), and these were long regarded as the earliest known mammal remains. Discovery of a nearly complete skull in the late Triassic of South China (Fig. 208) and critical restudy of the previously known genus *Tritilodon* have shown that these are still on the reptilian side of the fence, though possibly representing the group from which the multituberculates evolved.[6] At present, therefore, no mammals are known from Triassic rocks.[7]

FIG. 207. Lower jaw of a small mammal-like reptile, *Dromatherium*, from the Upper Triassic beds in North Carolina. After George G. Simpson. Twice natural size.

Return of Reptiles to the Sea. Marine reptiles are known in the Lower Permian rocks of South America and South Africa, but they did not become common until late in Triassic time. Dolphin-like reptiles called *ichthyosaurs* (Gr. *ichthys,* fish) appeared in the late Triassic seas and developed rapidly into one of the dominant groups of marine animals of the Mesozoic era. They were already abundant in the late Triassic of California and Oregon, where the largest species was about 30 feet long, and they were probably the largest animals in the world at that time. The ichthyosaurs had a fishlike contour with a laterally compressed tail and flipper-like limbs (Fig. 223). They were undoubtedly fast swimmers, able to capture fish or the ancient squids (belemnites) and ammonites of their time.

Another group of marine reptiles, the *plesiosaurs* (Gr. *plesios,* almost), made its appearance in Europe at this same time. Unlike the sleek ichthyosaur, the plesiosaur was a broad-bodied, short-tailed creature that paddled clumsily like a marine turtle (Fig. 224). He made up for this shortcoming, however, by a long and very agile neck, which enabled him to dart out his head and take by surprise unwary animals that came near.

Both ichthyosaurs and plesiosaurs were descended from land reptiles and represent two migrations back to the sea. The adaptation doubtless began in semiaquatic habits like those of the hippopotamus or the seal, but before the close of the Triassic both tribes of reptiles were remarkably adapted to a roving life in the open sea. The structure of the limbs proves their terrestrial ancestry, for it shows all the elements of the pentadactyl limb of a land animal, only changed in

FIG. 208. Oblique view of the skull of a mammal-like reptile, *Bienotherium*, from the late Triassic beds of South China, as restored by its discoverer, Dr. C. C. Young.

proportions so as to make finlike flippers instead of walking legs. It is a striking fact, confirming the expectation of evolutionary theory, that the limbs of the Triassic species are much more like those of land animals than are those of the more perfectly specialized forms of the Jurassic.

Marine Invertebrates. The seas now swarmed with ammonites (Pl. 13, figs. 6–14) of which there were many kinds, some far larger than any in the Permian. They were not only the most beautiful and characteristic shelled animals of the Mesozoic seas, but also the highest expression of invertebrate evolution in agility and strength. The rapid expansion of the group during the Triassic continued to near the close of the period, when a very rapid dying out almost caused their extinction. However, one genus (*Phylloceras*) with several spe-

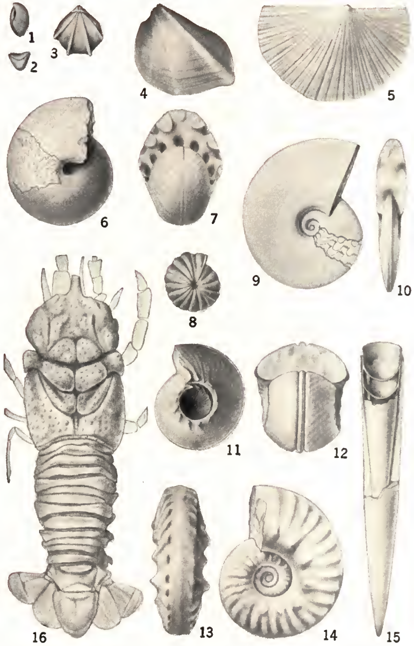

Plate 13. Triassic Brachiopods (1–3), Pelecypods (4, 5), Cephalopods (6–15), and Crustacea (16).

Figs. 1, 2, *Aulacothyris angusta* (side and front views); 3, *Tetractonella trigonella;* 4, *Myophoria kefersteini*, a forerunner of the Trigonias; 5, *Daonella americana;* 6, 7, *Paratropites arnoldi;* 8, *Leconteiceras californicum;* 9, 10, *Meekoceras gracilitatis;* 11, 12, *Tropites subbullatus;* 13, 14, *Ceratites spinifer;* 15, *Atractites macilentus*, the shell of a primitive belemnite broken to show internal chambered portion; 16, *Pemphix sueuri*, the oldest known lobster. All natural size. Drawn by L. S. Douglass.

cies managed to survive into the Jurassic and to give rise to another great evolution of forms in that period.

The decline of so great and adaptive a group is difficult to explain. Possibly they were unable to adjust themselves quickly to the attack of the rapidly evolving marine reptiles, which certainly preyed upon them.

Squidlike cephalopods (Pl. 13, fig. 15) appeared early in the Triassic and became very common in the Jurassic. Among the other molluscs, both *clams* (Pl. 13, figs. 4–5) and *gastropods* were in the ascendancy. Modern types of echinoids and starfishes, and small lobsters (Pl. 13, fig. 16) originated at this time but were not common until later.

Reef-building corals related to living kinds appeared in Late Triassic time and contributed to the thick dolomites and limestones of the Alps and the Himalayas. They were widely distributed through the Tethyan geosyncline of Eurasia and also spread along the Pacific coast of North America from California to Alaska. *Brachiopods* (Pl. 13, figs. 1–3), though still common in Tethys, had suffered a very great decline elsewhere from which they failed to recover. They were never afterward common in America.

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Chapter 15

THE JURASSIC PERIOD

During the Jurassic period epeiric seas gradually spread over Europe, with a life that was astonishingly rich and varied. In these seas there was deposited more than 3000 feet of the most richly fossiliferous of all the Mesozoic rocks. These have been the training ground for many European geologists, and have given us an understanding of some of the fundamental principles of stratigraphic geology.

Fig. 209. William ("Strata") Smith (1769–1839), "Father of English Geology."

It was here, for example, that William Smith first discovered the use of fossils in proving the age of the rocks and correlating those of the same age from place to place. Smith was a surveyor, concerned with mapping estates, draining swamps, and laying out canals across southern England, where the gently tilted Jurassic limestones and shales are superposed "like slices of bread and butter." Many of these beds were quarried for building stone and could be recognized by lithologic peculiarities from quarry to quarry. For years Smith collected the beautifully preserved fossils which weathered from these rocks, not with any appreciation of their significance but merely because they were curios—to him this was a hobby, just as the collecting of stamps or coins is to many another. However, as he was cataloguing his treasures one day in 1798, he perceived for the first time that a given bed always yielded the same kinds of fossils wherever he found it exposed, and that every other formation had different species. This being the case, he reasoned that he could identify the beds in other quarries by their fossils. As we have seen, it was only a few years after the discovery of this principle that stratigraphic geology had its great development in Europe, and that most of

the geologic systems were worked out and named. These advances would have been impossible without the principle discovered by Smith, who has been called the "Father of English Geology" (Fig. 209).

From the studies of the abundant Jurassic marine faunas came also the first clear ideas of climatic zones in the geologic past and of world paleogeographic maps.

Many of the Jurassic limestones in England are oölitic, and Smith therefore called this the "Oölite series"; but the German geologist, von Humboldt, and later the French geologist, Alexandre Brongniart, applied the name Jurassic to equivalent limestones in the Jura Mountains, between France and Switzerland. Smith's term is still used informally for part of this system in England, but the name Jurassic has long since gained universal acceptance for the system.

Jurassic History in America

Erosion Prevails in the East. In contrast to its great development in Europe, the Jurassic is more restricted than any other system in North America. Not a trace of these rocks is exposed east of the Great Plains, and it is probable that the entire eastern half of the continent was emergent and undergoing erosion throughout the period Nothing is known directly of the old borderland, Appalachia, but it probably began to founder and sink beneath the sea before the end of the Jurassic.

Undoubtedly the Appalachian region had considerable relief after the Palisade disturbance, but there is evidence to indicate that before the close of Jurassic time the whole region was essentially peneplaned.

Beginning of the Rocky Mountain Geosyncline. A new geosyncline took form during Jurassic time along the course of the present Rocky Mountains, and both ends of it were invaded by the sea (Fig. 210). The southern embayment, crossing Mexico, developed late in the period and reached northward to western Texas (Malone Mountains) and southeastern Arizona. Here the Jurassic formations are largely calcareous and bear ammonites indicating a direct connection with Europe but no close relation to the northern (Sundance) or the California seaways. This southern part of the trough is commonly known as the *Mexican geosyncline.*

The northern embayment is best known by the widespread Upper Jurassic formations which indicate an arctic sea spreading southward across Alberta and eastern British Columbia into the states of Mon-

Fig. 210A (left). Early Jurassic paleogeography. Symbols as in Fig. 154.

Fig. 210B (right). Middle Jurassic paleogeography.

Fig. 210C (left). Late Jurassic paleogeography. Jurassic overlap on the Gulf states is recorded in deep wells. The Mesocordilleran geanticline now separates the Sundance from the Columbian geosyncline.

tana, Idaho, and Wyoming, reaching for a short time as far south as central Utah and as far east as the Black Hills of South Dakota (Fig. 210*C*). In the northern Great Plains the chief marine record of this time is the *Sundance formation,* and for it this vast embayment has been named the *Sundance Sea.*

Middle and Lower Jurassic beds exposed locally about Fernie, British Columbia, indicate that the embayment temporarily reached this far south early in the period, but little is known of the distribution of these early deposits (Figs. 210*A*, *B*).

The middle part of this geosyncline was not submerged during Jurassic time, but much of Utah and parts of adjacent states subsided as an arid basin. Before the arrival of the Sundance Sea, thick desert sands had accumulated in Utah and Arizona, and during its stay the sediments continued to converge into it from the bordering uplands. Here, then, we find marine beds interfingering with desert deposits. The marginal lagoons at the south end of the Sundance Sea were from time to time land-locked and reduced to a highly saline condition, so that gypsum was precipitated. Thus, south of the limit of marine fossils, there are beds or lenses of gypsum interbedded in the continental sediments. Following the retreat of the Sundance Sea, the streams that crossed the basin from the rising lands farther west laid down over much of the geosyncline a mantle of alluvium that buried the most spectacular of all American dinosaurs. This is the *Morrison formation.*

The Jurassic period thus saw the beginning of the great geosyncline that dominated the western scene throughout the rest of the Mesozoic era and, during the Cretaceous period, was occupied by a vast sea that extended from the Arctic to the Gulf. Out of this trough the Rocky Mountains were formed at the close of the era, and for this reason it is known as the *Rocky Mountain geosyncline.*

Persistence of the Pacific Coast Geosyncline. The Californian and the Columbian geosynclines persisted, with minor changes, throughout the Jurassic period, and both received an impressive thickness of detrital sediment and much volcanic material. A chain of active volcanoes extended from California to southern Alaska during the early part of the period, and their activity was resumed on a grand scale during Late Jurassic time. Many of the volcanoes arose out of the seaways. In British Columbia submarine volcanics range up to 3000 feet in thickness, and in eastern California the Mariposa formation also includes immense outpourings of basic lava.

The seas which occupied these geosynclines were at times distinct, but during much of the period they were connected across eastern Oregon and Washington.

Nevadian Disturbance. Over much of the world the Jurassic lands were stable, but along the western border of North America, Late Jurassic time witnessed intense and widespread deformation accompanied by the intrusion of immense batholiths of granite. This orogeny has been named the *Nevadian disturbance,* but many American geologists think it deserves to be called a revolution.

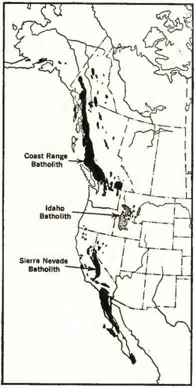

FIG. 211. Outcrops (*in black*) of the late Jurassic-early Cretaceous batholiths of western North America.

At this time the Pacific Coast geosynclines were crushed by compressive forces from the west, and their thick deposits were thrown into long ranges of fold mountains. The effects of the disturbance can be recognized as far east as the Wasatch Mountains in eastern Utah,[1] but the area of intense deformation was in western Nevada, California, Oregon, Washington, and the western part of British Columbia.

The distribution of the late Jurassic batholiths is indicated in Fig. 211. That of the Sierra Nevada is nearly 400 miles long and 80 miles wide; but the Coast Range batholith is still greater, extending for 1100 miles north of the Canadian border. Neither of the vast masses of granite is actually a single intrusion; each is a complex of closely related intrusions.* The emplacement of the granite probably followed shortly after the main folding and was a feature of the Nevadian disturbance. The net result of the compression and the intrusion was to leave the Jurassic and older rocks isoclinally folded and strongly

* The Coast Range batholith is, for the most part, not yet closely dated and may include intrusions of both late Jurassic and early Cretaceous date.

metamorphosed in eastern California and parts of British Columbia. The heat and pressure, as well as the gases and fluids ascending from such vast bodies of magma, led to severe metamorphism of the sedimentary rocks into which the intrusions were driven. The gold-quartz veins of the "Mother Lode" belt in the Sierra Nevada were formed by the ascending solutions, which penetrated the Jurassic slates then forming the roof of the batholith.

The precise date of the Nevadian disturbance is still uncertain. Like all great orogenic movements, this one undoubtedly developed over a considerable span of time, reached its climax, and then died away. It is unlikely, furthermore, that the climax came simultaneously over so vast a region. Since late Jurassic formations are involved in folding and intrusion that did not affect the Cretaceous formations, it is evident that the Nevadian disturbance culminated at the end, or near the end, of the Jurassic period.

Both the Mariposa formation of California and the Galice formation of Oregon, for example, are intensely metamorphosed, and both bear ammonites of Kimmeridgian age (next to the youngest in the Jurassic time scale of Europe). It is alleged by Taliaferro, however, that in Oregon the Galice formation is unconformably overlain by less deformed beds of the Knoxville formation, which bears fossils of Portlandian age (latest of the European Jurassic), and that here, at least, the climax of the disturbance came before the close of the period.[2] Much more evidence is needed to prove whether this relation is general in western North America.

Character of the Jurassic Formations

Redbeds and Dune Sands of the Colorado Plateau. Over the states of the Colorado Plateau the Jurassic system is represented by redbeds and dune sands that attain a maximum thickness of 3000 feet or more. The lower division has been named the *Glen Canyon group* for its magnificent exposures in the towering walls of Glen Canyon of the Colorado. The upper part is known as the *San Rafael group* for its exposures in San Rafael Swell, central Utah.

The *Glen Canyon group* is composed almost entirely of fine-grained pure quartz sand of light gray or pink color. The bedding is generally obscure, and the sandstone appears exceptionally massive. It is everywhere a cliff maker, outcropping in "unscalable walls of commanding height" (Figs. 200, 212). Near the middle of the group there is a zone of thin-bedded slabby sandstone which separates two mas-

sive formations, the *Wingate sandstone* below and the *Navajo* above. In the plateau region these normally outcrop in two colossal cliffs with a bench between. Over great areas the Navajo and Wingate formations are a solidified dune sand in which the swinging curves of gigantic cross-bedding betray eolian origin (Fig. 213). Rainbow Natural Bridge is carved from this sandstone.

These formations are almost entirely unfossiliferous, and their precise age is uncertain. Recently a small bipedal dinosaur was found in the Navajo sandstone near Kayenta, Arizona, and tracks of dinosaurs have been discovered at a few places in the slabby sandstone between the Wingate and Navajo formations. The Wingate sandstone may prove to be of late Triassic age.

CARL O. DUNBAR.

Fig. 212. Towering cliffs of Navajo sandstone, Zion National Park, Utah. In the distance at the left, The Great White Throne.

The *San Rafael group* is formed of red sandstones and siltstones and red shales into which there interfinger from the northwest two great wedges of gray marine shales and sandstones. It also includes one massive pure sandstone member like the great dune sands below. The redbeds were deposited on a low alluvial plain in an arid basin, and the marine members that interfinger from the northwest mark temporary incursions of the Sundance Sea. The group has a thickness of about 1500 feet.

All these formations of both the Glen Canyon and the San Rafael groups thin out by overlap on the old Pre-Cambrian granite of the Uncompahgre Plateau and other elements of the Colorado Mountains in western Colorado. The increasing coarseness and the presence of locally derived boulders indicate that much of this detrital material was coming from that region; but, since the sandstones thicken toward the west, it is probable that the Mesocordilleran geanticline lying

CARL O. DUNBAR.

Fig. 213. "Frozen dunes" in the Navajo sandstone near the south entrance to Zion National Park, Utah.

C. H. DANE, U. S. GEOLOGICAL SURVEY.

Fig. 214. Upper part of the Morrison formation near Cisco, Utah, comprised of variegated shale and sandstone.

between the Rocky Mountain and the Californian seaways (Figs. 210*C*, 230*B*) was supplying a large share of the sediment.

Marine Strata of the Sundance Seaway. The Sundance formation of the northern Great Plains is a conspicuous key horizon, lying between the unfossiliferous redbeds of the Triassic and the continental sediments that rest upon it. Over this area it is normally only 200 to 300 feet thick. It consists mostly of sandstone and shale, but there are limy zones filled with fossil oysters and other clams, as well as the shells of belemnites and other cephalopods, and, rarely, skeletons of ichthyosaurs. The water was evidently shallow, since the sediments varied locally from nearly pure sand to mud. In places the shales are partly red.

Traced westward into Idaho, the Jurassic beds thicken to 5000 or 6000 feet and are divisible into four distinct formations. This great increase in thickness is due partly to the fact that deposition began earlier and continued longer in the geosyncline than it did farther east. It may be also that more rapid subsidence allowed the sediments derived from the west to come to rest more readily on the floor of the geosyncline, so that accumulation there was more rapid.

Morrison Formation and Its Dinosaurs. All the gigantic dinosaurs of the American Jurassic have come from a single formation (Figs. 214, 215) that was deposited as a blanket of fluvial sediments over the rest of the Jurassic formations in the Cordilleran region. The formation is named for its exposure at Morrison, near Denver, but it extends far to the north into Montana, west into Utah, and south into New Mexico, originally covering more than 100,000 square miles of the Rocky Mountain region. In spite of this great extent, it is usually less than 400 feet thick.

The Morrison consists of shales, siltstones, and sandstones with local conglomerates, all of which intergrade laterally, as is the habit

BARNUM BROWN, AMERICAN MUSEUM OF NATURAL HISTORY.

Fig. 215. Excavating a dinosaur skeleton in the Morrison formation near Shell, Wyoming.

of continental deposits, so that it is impossible to follow a single bed over a considerable distance. The coarser sediments are commonly irregularly bedded and cross-laminated. The color varies locally from greenish-gray to black or lavender or pink or even white. No marine fossils have ever been found, but more than 150 kinds of terrestrial animals and land plants are known from these beds. These include the greatest of all dinosaurs. Sixty-nine of the species are dinosaurs, 25 are tiny primitive mammals, 3 are crocodiles, 24 are river clams and land snails, and 23 are plants.

From these facts we can picture the region at the time of deposition in a setting not unlike that of the present basins of the Amazon or Paraná rivers. It was a low alluvial plain crossed by sluggish streams heading in the distant highlands to the west, whence came heavy loads of mud and sand. Here and there swamps or small lakes interrupted the courses of the braided streams. The shifting sands and gravel bars along the channels gave rise to deposits of cross-bedded sandstone and conglomerate, while the finer mud and silt that settled over the floodplains produced the varicolored shales. The climate had become more humid with slight emergence of the whole region from the sea, so that vegetation spread over the landscape and animal life was abundant. In southwestern Colorado and New Mexico the lower part of the section generally assigned to the Morrison includes eolian sand and gypsiferous beds, but these are now known to be equivalent to part of the Glen Canyon group and older than the Morrison formation proper.[3]

The geologic date of this formation is difficult to prove. It overlies beds (Sundance) dated certainly as early Late Jurassic and is in turn overlapped (in Oklahoma and southeastern Colorado) by beds of late Early Cretaceous age (Washita). So far as the stratigraphic evidence goes, therefore, the Morrison may be Late Jurassic or Early Cretaceous. The fauna, though abundant, can not be compared with anything in the standard marine sections of the world, and we still know little about the land life of the Late Jurassic and Early Cretaceous of America except what is recorded in the formation in question. A comparison of the dinosaurs of the Morrison with those of the Jurassic and Cretaceous of Europe, however, brings out rather convincing evidence of Jurassic affinities (especially among the Stegosauria), and this is supported also by a comparison of the mammals.[4]

Curiously, the best evidence on the age of the Morrison is found nearly half-way around the Earth, in East Africa, where there are

beds bearing dinosaurs closely like those of the Morrison, interbedded with marine zones carrying undoubted Jurassic ammonites. Although it is possible that the Morrison and the East Africa (Tendaguru) formations are not strictly equivalent, the balance of the evidence favors the assignment of the Morrison to the Late Jurassic.

Rocks of the Pacific Coast Geosyncline. Jurassic rocks are extensively exposed in California but in widely separated areas where they have escaped the several later periods of deformation and deep erosion. In most places, they have become involved in very complex structures and metamorphosed to such an extent that fossils are obscure. With these fragments of the record, it is impossible to restore a complete picture of the Jurassic history of California. Suffice it to say that the sediments were very thick and almost entirely detrital, proving that the bordering lands were sufficiently elevated to be undergoing extensive erosion.

In eastern California the *Mariposa slates* and interbedded volcanics reach a thickness of possibly 10,000 feet. Mount Jura at the northern end of the Sierra Nevada presents a very complete Jurassic section, with fifteen formations ranging from Lower to Upper Jurassic and containing volcanic tuffs and agglomerates of various ages throughout the period; and recently a still finer and more complete section was discovered in eastern Oregon. In Shasta County, California, the Jurassic is represented by the *Knoxville* sandstone and shale, which may total 10,000 feet in thickness, and includes continental beds with land plants, as well as marine zones with the peculiar arctic clam, *Aucella* (Pl. 14, fig. 6). The *Franciscan series,* which is widely spread in the Coast Ranges both north and south of San Francisco, contains radiolarian cherts and interbedded sandstones probably of middle and later Jurassic age, with an estimated thickness of 15,000 feet. These sediments become coarser toward the west, suggesting their origin from the marginal land, Cascadia. In the vicinity of Vancouver Island, also, thick detrital Jurassic formations are found.

The great thickness and the detrital nature of all these western formations show that the disturbance culminating in the Nevadian mountains was already being felt during Late Jurassic time, and that the Pacific Coast geosyncline was profoundly depressed as the bordering geanticline arose.

Southern Alaska has a great development of Jurassic rocks, though they have not been studied in detail. Marine formations of Early,

Middle, and Late Jurassic age are known, and much volcanic material is associated with these, especially in the lower and upper portions.

Climate

As we have seen, desert conditions continued in the southern part of the Cordilleran region, where the Navajo sandstone is one of the greatest dune-sand formations of the entire Earth. This, however, was apparently a local condition and may have been due to the fact that the region was lower than the western land mass which cut off the moisture-bearing winds. In many other parts of the world, the climate was decidedly more humid than it had been in the Triassic, and gray or dark sediments with coal beds accumulated in the lowlands. For example, the Middle Jurassic is coal-bearing in Mexico, California, Alaska, Greenland, Spitzbergen, Europe, Siberia, India, China, Australia, South Africa, and Antarctica. There was nothing like the wide distribution of redbeds that we observed in the Triassic, and no important salt or gypsum deposits are known like those of the two previous periods. Outside of North America the epeiric seas were again very extensive, and with this spread of marine water went, apparently, milder and moister climate.

The temperature appears to have declined somewhat at the close of the Triassic, though not enough to bring on glaciation. The middle and later parts of the Jurassic, on the contrary, were marked by very mild climate even in high latitudes, and probably by subtropical conditions over most of the United States and southern Europe.

The lowering of the temperature at the end of the Triassic is inferred from the great decline of the ammonites, the dwarfing of the Early Jurassic insects, a decided reduction and geographic restriction of the reef corals of Early Jurassic time, and the marked development of growth rings in the woods of that time in temperate latitudes.

That the Middle and Late Jurassic climates were milder and more equable than the present ones must be inferred from the distribution of both animals and plants. Toward the close of the period the greatest of all dinosaurs ranged over the western United States at least as far north as Montana, and in Asia they were at home in Mongolia, where winter temperatures now fall far below zero. Yet the dinosaurs very probably could not endure freezing weather. Reefs of corals, sponges, and bryozoa abound in the Jurassic rocks, corals occurring some 2000 miles north of the present range of similar forms. The distribution

and character of the Mid-Jurassic land plants are thought also to indicate a warm, moist climate over much of the Earth. Furthermore, the insects of the early Upper Jurassic formations are much larger than those of the Lower Jurassic.

Economic Resources

Coal. The Jurassic is an important coal-producing system, if we consider the world at large. Extensive areas in Siberia are underlain by Jurassic coal of economic importance, and in Tasmania and Australia the chief coal measures are the Jurassic rocks. There are also important coals in Spitzbergen and smaller deposits in various parts of Europe and southern Asia. In North America, however, there is no workable Jurassic coal except that of eastern Greenland.

Gold. The gold that attracted the "Forty-Niners" and led to the rapid settlement of California has its source in the gold-quartz veins formed in the Jurassic slates along the western slope of the Sierra Nevada. The placer gold that the early settlers panned from the streams was concentrated in the river gravels during Cenozoic times, but it came originally from the Jurassic veins and was freed during their erosion. A long, narrow belt of Jurassic rocks containing gold veins and extending for 120 miles along the western foothills of the Sierra Nevada is called the "Mother Lode" belt.

Up to 1937, California had produced about $1,850,000,000 worth of gold, most of which came from the veins of late Jurassic origin or from placers derived therefrom. In 1939, the state produced 1,424,719 ounces of gold with a value of $49,865,000, which is approximately one-third of the production of the entire United States.

Life of the Jurassic Period

Forests of Evergreens. The floras of the Jurassic, although in the main a continuation of those of the Late Triassic, were in important respects different from modern ones. So far as known, they consisted of scouring rushes, herbaceous and tree ferns, cycadeoids, gingkos, and abundant conifers (Fig. 216). The forests presented thick stands of pines and other conifers, mingled with gingkos and tree ferns, with an undergrowth of herbaceous ferns and rushes, while the more arid slopes presented an open growth of cycadeoids and ferns. It seems to have been an evergreen assemblage, still lacking the deciduous hardwood trees like those of our modern forests, though it probably in-

cluded forerunners of these, as yet unknown. Modern flowering plants, that is, angiosperms, are not certainly known from the Jurassic, though a few inadequately known types have been suspected of representing this great group. The cycadeoids, however, were truly flowering plants.

A remarkable feature of the Mid-Jurassic floras is the wide distribution of many of the species. If we exclude the cycads, about half the plants known in North America are found also in Japan, Manchuria, Siberia, arctic Alaska, Spitzbergen, Scandinavia, or England. Even the plants collected by the Shackleton expedition in Louis Philippe Land below Cape Horn (in latitude 63° S.) are practically the same as those of Yorkshire, England. In this cosmopolitan distribution of the land plants, there is striking testimony of mild, equable climates.

Cycadeoids (Figs. 216–218) appear to have been the most characteristic plants of the Jurassic, as they were of the Triassic. In fact,

YALE PEABODY MUSEUM.

Fig. 216. A Jurassic landscape. Part of a great mural by Rudolph Zallinger. Plants: 1, a fern, Matonidium; 2, scouring rush, Equisetites; 3, a tall-stemmed cycadeoid, Williamsonia; 4, Cycadeoidea; 5, a conifer, Araucarites. Animals: 6, a minute dinosaur, Compsognathus, only about 2 feet long; 7, a plant-feeding dinosaur, Camptosaurus; 8, a large carnivorous dinosaur, Allosaurus; 9, a plated dinosaur, Stegosaurus; 10, a giant sauropod dinosaur, Brontosaurus (length 65–70 feet); 11, a pterosaur, Rhamphorhynchus; 12, the first bird, Archaeopteryx.

the Early Mesozoic has been characterized as the *Age of Cycads.* Although the cycadeoids have persisted until the end of the Mesozoic era, and are locally abundant in the Cretaceous rocks, they were eclipsed after Jurassic time by the great expansion of the modernized plants.

Yale Peabody Museum.

FIG. 217. A living cycad.

Medieval Insects. About one thousand kinds of insects are known from the Jurassic rocks, and among these we note representatives of most of the modern orders. Caddis-flies, scorpion-flies, dragonflies, and beetles were common; grasshoppers, cockroaches, and termites or white ants were also present; moths (Fig. 219) and flies (Diptera) made their appearance at this time; and even the social ants were represented. Since the last three groups represent the most highly specialized stocks of the insects, it is clear that the significant features of insect evolution had already appeared by the middle of the Mesozoic era.

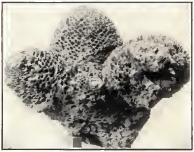

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FIG. 218. Three-branched trunk of the cycadeoid, *Cycadeoidea marshiana*, from the Lower Cretaceous (Lakota sandstone), Cycad National Monument, Black Hills, South Dakota. Courtesy of G. R. Wieland. The specimen has an extreme width of about 25 inches.

Reptile Hordes. By Jurassic time the *Age of Reptiles* was in full swing. Not content with a complete domination of the lands, some of the reptiles anticipated the birds in flight, and others excelled the fishes in the sea. The dinosaurs had attained their greatest size in ponderous sauropods so enormous that 60 to 75 individuals in circus parade would have spanned a mile. Never before or since has the Earth been so completely under the sway of reptilian hordes.

Dinosaurs were now in their heyday, and four of the five great tribes of these reptiles were represented. Sauropods were the largest and

most distinctive. *Brontosaurus* (Figs. 216, 220), one of the best-known American forms, reached a length of about 65 feet, but the more slender *Diplodocus* had a length of nearly 80 feet; the brain of each of these huge animals, however, weighed less than a pound. Until recently sauropods were almost unknown outside the Jurassic rocks, but now they have been found in the Lower Cretaceous of Wyoming, and in the Upper Cretaceous of New Mexico, Utah, and Texas.

The plated dinosaur, *Stegosaurus* (Figs. 216, 221), with a 2½-ounce brain for 10 tons of weight, was equally distinctive of this time. In addition, there were bipedal carnivores of large and small size, one of which, *Compsognathus,* must have been as agile and slender as a small kangaroo, for it was only 2½ feet long. Of the larger carnivores of this period, *Allosaurus* (Fig. 216) was perhaps the greatest, having a length over all of more than 30 feet. Still larger species lived in the Late Cretaceous.

FIG. 219. A Jurassic moth, *Limacodites mesozoicus*, as restored by A. Handlirsch. About ⅔ natural size.

The herbivorous bipeds (ornithopods) are known from several genera but were less common here than in the Cretaceous.

Among the most bizarre animals of the Mesozoic were the *pterosaurs* (Figs. 20, 216, 222) or winged reptiles which "laid claim to the empire of the air in those medieval times." With leathern wings and naked bodies, they must have presented a batlike appearance, though the structure of their wings shows how superficial this resemblance was. The bat is a warm-blooded animal allied to the other mammals, but the pterosaur was a reptile. The bat has all its digits extended to bear the weblike wing membrane, whereas the pterosaur had only the fourth finger greatly extended to support the wing, leaving the other digits free to serve as claws. The Jurassic species had sharp, slender teeth, and heads that were decidedly reptilian. Some had long tails with flukes, which probably aided in keeping the balance during flight, but other forms were tail-less. In the Jurassic pterosaurs the front and hind limbs were not greatly disproportionate in size, and it is clear that these winged dragons developed from quadrupedal land reptiles. Upon alighting, they certainly walked on all fours (see Fig. 222).

During the Jurassic period, the pterosaurs ranged in size from minute species with a wing spread equal to that of a sparrow up to

others that spanned 3 or 4 feet from tip to tip of wings. The greater and more highly specialized forms followed in the Cretaceous period.

In the seas, both *ichthyosaurs* and *plesiosaurs* were at the zenith of their development. The former, with their streamline contour and powerful fluked tail, must have been efficient swimmers (Fig. 223). They certainly resembled the modern porpoise to a remarkable degree, except that their tail flukes were in the vertical plane, so that they swam by a lateral instead of a vertical motion. The resemblance is purely superficial, however, for the porpoise is a warm-blooded animal and a mammal.

In the Lower Jurassic black shales of Germany, remarkably preserved specimens of ichthyosaurs are found with the entire skeletons articulated and surrounded by a carbonized film that outlines the con-

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Fig. 220. Skeleton of Brontosaurus. This specimen, from the Morrison formation at Como Bluffs, Wyoming, measures 67 feet from nose to tip of tail and stands about 18 feet high at the hips. A reconstruction may be seen in Fig. 216.

tour of the flesh (Fig. 18, p. 38). Some of these, moreover, have been found with unborn young inside the rib case, proving that they were viviparous. In this respect the ichthyosaurs show a more perfect adaptation to aquatic life than any other known reptiles, for even the great marine turtles come ashore to lay their eggs. The Jurassic species were rather smaller than some of the Triassic forms, rarely attaining a length of 25 feet. Many were mature at a length of 5 to 10 feet. They fed on fish and cephalopods. A remarkable skeleton found with some 200 belemnite shells inside suggests that they were especially fond of these squidlike animals.

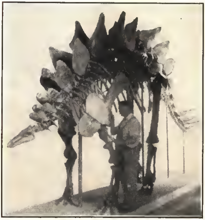

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FIG. 221. Skeleton of the plated dinosaur, *Stegosaurus ungulatus*, from the Morrison formation at Como Bluffs, Wyoming.

Plesiosaurs (Fig. 224) are also best known from the Jurassic rocks. In these reptiles the tail was not fluked, and propulsion was by means of the paddle-like flippers, as in the marine turtles. The largest Jurassic species scarcely exceeded a length of 20 feet.

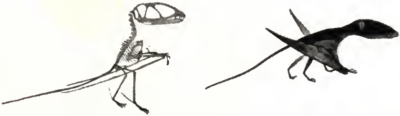

FIG. 222. *Dimorphodon macronyx*, a small pterosaur from the Lower Jurassic in Lyme Regis, England. Left, skeleton in bipedal attitude; right, flesh restoration in quadrupedal attitude. The animal had an extreme length of slightly more than 3 feet. From Seeley, *Dragons of the Air* (D. Appleton and Company).

Slender-snouted *crocodiles* much like the modern gavial of India were abundant in the seas as well as in the rivers. Marine *turtles* also were present, though less common than the groups of reptiles already mentioned.

First Birds. Birds appear as fossils for the first time in Upper Jurassic rocks and represent one of the most remarkable advances that the life of this period has to show. As yet only three specimens are known, and these are from the famous lithographic stone quarries about Solenhofen, Bavaria. Two of these are fine skeletons with impressions of the feathers. The third specimen is the impression of a single feather. The two skeletons seem to represent different genera and species, though both are about alike in size and general features.

To the first-discovered bird was given the appropriate name *Archæopteryx* (Gr. *archaios*, ancient, + *pteron*, wing). It was a strange creature, more reptile than bird, and yet because of its feathers distinctly to be classed as a bird. It would be difficult to find a more perfect "connecting link" between two great groups of animals, or more cogent proof of the reptilian ancestry of the birds.

Archæopteryx (Figs. 216, 225) was about the size of a crow. Three remarkable features strike one at the first glance: (1) the jaws were set with a row of small teeth. These were not mere serrations on a horny beak but true conical teeth set in individual sockets like those of many reptiles. (2) In the wings the digits were not completely fused, and the first three still functioned as claws. (3) The tail was long and slender, with the feathers diverging pinnately from its axis and not fanwise as in modern birds. The plumage was thoroughly birdlike, but the teeth, clawed wings, and long tail betray reptilian affinities.

First Mammals. The most significant advance in the life of the Jurassic was the appearance of the primitive mammals (Fig. 226).

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Fig. 223. The marine reptile, Ichthyosaurus, with a brood of young. From a painting by Charles R. Knight. The adult was about 10 feet long.

Fig. 224. The marine reptile, Plesiosaurus. A pair of plesiosaurs in the foreground, with ichthyosaurs in the right background and fish in the left foreground. After E. Fraas, Stuttgart Museum.

Although small and unimpressive, they represent the early development of the warm-blooded animals which now dominate the Earth, and the group to which man himself belongs. None of the Jurassic mammals was larger than a very small dog, and their known remains are quite fragmentary, consisting mostly of jaws, isolated teeth, and portions of limb bones. Nevertheless, they are represented in North America, Europe, and Africa and probably ranged over all the continents except Australia. Most of the fossil remains have been found in association with dinosaurs. The American forms have all come from the late Jurassic (Morrison), and most of them from a famous dinosaur quarry at Como Bluffs, Wyoming. The rest have been recovered mostly from Middle and Late Jurassic beds in England.

In spite of their small size, these early mammals already showed marked specialization in their teeth, suggesting a wide variation in habits of life. Among the Jurassic species, four orders can be recognized, all originating in theriodont reptiles. All four of these early mammalian stocks are now extinct, but one of them (Pantotheria)

appears to have given rise during the Mesozoic to the modern marsupials and placentals; the others died out without descendants. Although, on theoretical grounds, the obscure little egg-laying mammals (monotremes) now living in Australia and Tasmania would seem to represent the most primitive possible stage of mammalian development, there seems to be no basis for the inference that the Jurassic mammals were also egg-laying. The monotremes may have developed independently of the other mammals out of ancient reptiles (Theriodontia).[5] Their geologic history is completely unknown.

Marine Invertebrates. The profusion of marine invertebrates and the richness of their fossil remains in the Jurassic rocks have already claimed our attention. In many respects these faunas were essentially modern. For example, *corals* of the modern families were then extensive reef makers, and abundant *pelecypods* (Pl. 14, figs. 6, 7) and *gastropods* resembled modern forms in general features. True *oysters* had already become common, though strongly plicate species were more prominent then than now. Lobsters and shrimplike *crustaceans* were present in numbers, and one depressed form (*Eryon*) foreshadows the evolution of the crabs (Fig. 227). The *crinoids*, locally abundant, resembled either of two modern types: the large stalked forms were closely allied to the *Pentacrinus* that still lives in deep water off the

Fig. 225. The oldest known bird, Archæopteryx. Although here restored as feeding on fruit of the cycad, it was probably carnivorous. The bird was about the size of a crow. From the Upper Jurassic at Solenhofen, Germany. After G. Heilmann.

Japanese coast, while small stemless species were like *Comatula*. *Sea-urchins* of modern aspect were well represented (Pl. 14, figs. 1, 2), and among these were the first of the "heart-urchins," but there were no "sand dollars," the latter having evolved after the Cretaceous. *Sponges* were in places important reef makers.

More prolific and more distinctive than all other kinds of shellfish, however, were the *ammonites* (Pl. 14, figs. 9–11), which now attained the zenith of their career and were represented by a vast number of

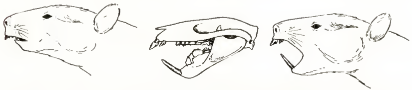

FIG. 226. One of the best-known Jurassic mammals, *Ctenacodon*, from the dinosaur quarries in the Morrison formation at Como Bluffs, Wyoming. It belongs to the extinct order Multituberculata. The skull and two views of the head (about natural size) as restored by G. G. Simpson.

kinds, some large and some small, but all possessing delicate pearly shells. The intricacy and the variety displayed in the fluting of the ammonite septa during this period are remarkable, and the modification of bodily form of the living animals is an eloquent commentary on the plasticity of animal life. Some species, with slender shells coiled like a rope and with the living chamber occupying more than an entire volution, must have had bodies of eel-like proportions, whereas others with broadly rounded, globular shells had bodies as short as the octopus. The most remarkable of all modifications must have existed in those species with laterally compressed and deeply involute shells wherein the penultimate whorl of the shell was so deeply impressed in the animal's back as to divide it almost in two.

The *belemnites*, some of them 5 or 6 feet long, were also at their climax at this time, and their cigar-shaped internal shells are extremely common fossils (Fig. 228, and Pl. 14, fig. 8). Rare specimens found in the black shales of the Lower Jurassic in England and Germany show the form of the body and arms, preserved as a carbonized film about the shells. From these it is certain that the belemnites were squid-like cephalopods with six instead of ten arms and with corneous hooks instead of sucking discs on the arms. It is almost certain that true *squids* were also evolving from common ancestors

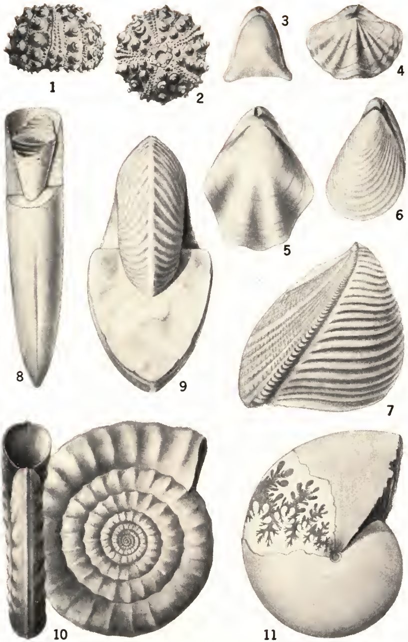

Plate 14. Jurassic Echinoids (1, 2), Brachiopods (3–5), Pelecypods (6, 7), and Cephalopods (8–11).

Figs. 1, 2, *Hemicidaris intermedia* (side and upper views); 3, *Digonella digona;* 4, *Spiriferina walcotti,* last of the spiriferoids; 5, *Goniothyris phillipsi;* 6, *Aucella piochii;* 7, *Trigonia costata;* 8, *Belemnites densus* (broken to show chambered shell); 9, *Cardioceras cordiforme;* 10, *Echioceras raricostatoides;* 11, *Phylloceras heterophyllum.* All natural size. Drawn by L. S. Douglass.

with the belemnites, but their shells were too perishable to have left an imposing record like that of the belemnites. It is interesting to note that an ink sac exactly like that of modern squids was present in the Jurassic forms and that the pigment is sufficiently preserved in some of the Lower Jurassic specimens mentioned above so that ink can still be made of it.

Solenhofen, a Remarkable Fossil Locality. In the region about Solenhofen, Bavaria, the Upper Jurassic rocks include circular reefs of sponges and corals within which there are deposits of very pure, fine-textured limestone. For generations this stone has been quarried and shipped to all parts of the world for the engraving of etchings and lithograph prints. During this time the quarries about Solenhofen and Eichstadt have yielded more remarkable fossils than any other locality in the world.

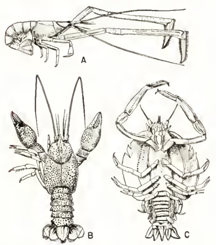

FIG. 227. Crustaceans from the Upper Jurassic limestones at Solenhofen, Bavaria. *A*, ghost-shrimp, *Mecochirus; B*, lobster, *Eryma; C*, a flattened, crablike form, *Eryon*. After A. Oppel.

The flawless, fine texture of the Solenhofen stone, so essential for the reproduction of the lights and shades in lithographs, lends itself equally well to the preservation of the delicate impressions of organic tissues. It has therefore given us a knowledge of many soft-tissued Jurassic animals, such as jellyfish, and has preserved impressions of the fleshy bodies of creatures otherwise known only from their skeletons or shells. From these quarries, for example, came all the known specimens of Jurassic birds. The faithful impression of their delicate feathers is a fortunate thing, for without this evidence it would be difficult to prove that *Archæopteryx* was not a reptile. Here also have been found specimens of pterosaurs in which the form of the delicate wing and tail membrane (Fig. 20) are preserved with remarkable fidelity. Among other things rarely preserved elsewhere are 8 kinds of jellyfish and more than 100 species of insects, including moths and flies. Finally, very good specimens of the horseshoe crabs (*Limulus*) occur here. A total of 450 species of animals has been recovered from these quarries.[6]

Evidently these are the deposits of lagoons within atolls that lay not far from the mainland. The fossils include a dinosaur, 29 species of pterosaurs, and 3 birds. On the other hand, there are no fresh-water animals, and marine fishes and marine invertebrates (mainly crustaceans and ammonites) comprise nearly all the fauna. One remarkable feature of the deposit is that most of the organisms were not dismembered before burial. There were certainly no scavengers living on the bottom, and the entombed creatures were either dead when

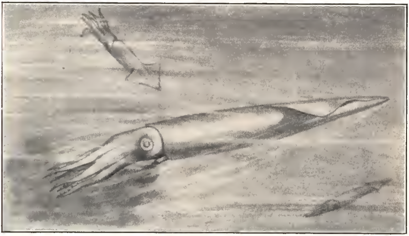

Fig. 228. Reconstruction of a belemnite, darting backward and discharging a smoke screen of ink. Such animals ranged from a few inches to 5 or 6 feet in length. The internal shell of a belemnite is shown in Pl. 14, fig. 8.

they were washed over into the lagoon or died soon thereafter and were quickly buried by the fine limy ooze that spread in from the fronts of the reefs. It is because of this quick burial that the animals are so well preserved. The floor of the lagoon may have been in part permanently submerged and in part only a mud flat covered twice daily by the tides.

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Chapter VII has an account of the discovery of the great Jurassic dinosaurs in Colorado and Wyoming in 1877.

CHAPTER 16

CRETACEOUS TIME AND THE END OF AN ERA

General Features. The name Cretaceous (Lat. *creta,* chalk) was first applied to the extensive formations of chalk that form the white cliffs on both sides of the English Channel (Fig. 229). Gradually the term was extended to embrace closely related strata of other kinds

Carl O. Dunbar.

FIG. 229. Chalk cliffs at St. Margaret on the Straits of Dover, England.

until it included all the rocks between the Jurassic and the base of the Cenozoic. The Cretaceous has thus become one of the greatest geologic systems, widely distributed in many countries and commonly very thick. Considering the world as a whole, this was probably the age of greatest submergence of the continents and the most extensive epeiric seas the Earth has known.

It is remarkable that most of the chalk deposits of the Earth were formed during this single period, yet other types of sediments

Fig. 230A (left). Early Late Cretaceous paleogeography (time of the Dakota sandstone). Areas of nonmarine deposits are marked by black line shading.

Fig. 230B (right). Middle Late Cretaceous paleogeography (during deposition of the Benton shale). Note the extensive nonmarine deposits along the east side of the Mesocordilleran geanticline.

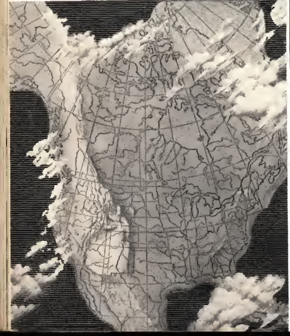


Fig. 230C (left). Paleogeography at the close of the Cretaceous period during the Laramide deformation.

laid down at this time vastly outbulk the chalk in most regions. In this respect the term Cretaceous is a misnomer, but it has never had a rival since first proposed in 1822, and is now in universal use.

During the present century there have been varied attempts to subdivide this great system into two, but no general agreement has been reached as to a natural line of separation. In America, two subdivisions, Lower and Upper Cretaceous, are commonly recognized; however, the retreat of the sea from Kansas to southern Texas at the close of Early Cretaceous time may be interpreted as an incidental though marked oscillation in a great cycle of continental submergence. Moreover, in southern Europe and in Mexico, a threefold instead of a twofold division seems more natural, and the planes of division do not accord very well with those in the United States. In any event, the Early Cretaceous history may be looked upon as an introduction to that of the Late Cretaceous, and we shall here present the record as that of a single, long, and complex period.

Physical History of North America

The Last Great Submergence

Early in Cretaceous time the sea began to spread over the continent, first from the Gulf of Mexico through the Mexican geosyncline into the southern United States, next from the Arctic into the Rocky Mountain trough, and finally across both the Pacific and Atlantic margins of the continent. With an irregular and pulsing advance, the interior seas gradually united and submerged almost 50 per cent of North America, forming at their culmination one of the greatest marine floods of all time (Fig. 230*B*). The climax came shortly before the middle of the Late Cretaceous epoch, and thereafter the interior sea retreated southward, was gradually silted up, and finally disappeared near the close of the period. This was the last extensive submergence North America experienced, for in Cenozoic time the continent had its present outline and almost its present size.

Atlantic and Gulf Overlap. Marine Cretaceous rocks, succeeding nonmarine beds, underlie the entire Coastal Plain from New Jersey to Texas, proving extensive submergence of the present coastal belt during the early part of Late Cretaceous time. These marine formations overlap across the land, in many places passing into brackish-water or nonmarine beds in the landward direction, but grading into finer-grained marine strata toward the sea. The sediments clearly

came from the present land mass and were spread eastward and southward over a shallow sea floor like the present shelf.

Herein is a striking contrast with all the older marine deposits of eastern North America, for the latter had spread westward from the marginal land, Appalachia, into a geosyncline that lay within the continent. Some time during the Jurassic, eastern Appalachia had foundered beneath the sea, and now, *for the first time in all the ages, the waves of the Atlantic were breaking against the margin of the present continent.* During Early Cretaceous time the old land of Llanoria also continued to sink beneath sealevel, and the Gulf of Mexico, spreading across it, began to take form, though probably as a much shallower and far greater seaway than at present. During Late Cretaceous time (Fig. 230*B*) the head of the Gulf was at least as far north as Cairo, Illinois, that is, 600 miles farther north than today. Its western shoreline lay in central Arkansas and Oklahoma, and its eastern margin encircled the southern end of the Appalachian folds in central Alabama and Georgia, probably inundating all of Florida. Also, most of the larger Antillean islands, Central America, and Mexico were submerged.

Filling of the Rocky Mountain Geosyncline. The broad Rocky Mountain trough was gradually submerged until it formed a vast seaway nearly 1000 miles wide and three times as long, completely dividing the continent into two land masses (Fig. 230*B*). Its flooding records a long and gradual diastrophic cycle, for the slow submergence was followed shortly by a long emergence.

The sea occupied the Mexican trough first, soon overlapping most of Texas. It did not reach northward beyond Texas, however, until toward the end of Early Cretaceous time (Washita epoch), when a temporary pulsation sent it across Kansas, Nebraska, and Colorado into Iowa and Montana. At about the same time the Arctic sea began to invade the northern end of the geosyncline. A considerable retreat, following this advance, made a break in the sedimentary record in both the northern and southern sequences, and this fact has been used by some geologists as the basis for separating the Lower from the Upper Cretaceous as a distinct system. The placing of so much emphasis on this break, however, has not been widely accepted, and we here retain the old view, regarding the Lower and Upper Cretaceous as of one period. Soon after the middle of the period (Fig. 230*B*) the southern and northern embayments met and flooded the entire region of the present Rockies and the Great Plains. Even the granitic domes of the Colorado Mountains were submerged

in a sea that stretched from central Utah and southeastern Idaho to the plains of easternmost Minnesota and central Iowa.

Soon after this maximum inundation the northern end of the geosyncline emerged, and the great epeiric sea began a southward retreat, hastened by the rapid filling of its basin with sediments which poured in, in ever-increasing volume, from rising highlands farther west. The final retreat of the sea transformed its old floor into a vast swampy lowland over which the western streams spread thick nonmarine sediments during the closing stages of the period. In the swamps of this lowland accumulated the vegetation that was to make the vast coal beds of the latest Cretaceous formations of the Rocky Mountains region from Alberta to Mexico.

Pacific Coast Overlap. West of the Rocky Mountain geosyncline lay the Mesocordilleran geanticline (Fig. 230*B*) which had risen into mountains at the close of the Jurassic. Still farther west there was a coastal belt involving much of the old Pacific Coast geosyncline of California and the western part of British Columbia. Apparently, Cascadia was being submerged or had already subsided, and the Pacific shelf sea was spreading over the coastal belt from the peninsula of Lower California northward to Alaska. This region in California was further broken by numerous north-south faults, and the unequal but rapid subsidence of some of the narrow fault blocks quickened the accumulation of very thick deposits of detrital sediments.

Continued Rise of the Mesocordilleran Axis

The Mesocordilleran geanticline was a rather narrow but rugged land mass throughout the period, shedding great quantities of detrital sediments both west and east. At the beginning of the period it was a bold mountain chain, and the effects of later denudation were largely counteracted by repeated though irregular uplift, as the bordering geosyncline on the east deepened. Much of this uplift may have been of the nature of gentle warping, but there is evidence of sharp uplift with some folding and marked volcanism in California about the close of the Early Cretaceous.

The geanticline must have bristled with active volcanoes during much of the period, and especially during the last half, for there are many layers of *bentonite* (a rock made of altered volcanic ash) interbedded in the Cretaceous formations of the northern Great Plains which bear witness to heavy falls of volcanic dust that spread eastward as far as Nebraska and Kansas.

Laramide Revolution and the Birth of the Rockies

Extended crustal unrest marked the closing stages of the Mesozoic era in many parts of the world, but nowhere with more profound and far-reaching effect than in the western half of North America. At this time the floor of the great geosyncline, so recently covered by the Cretaceous sea, became the scene of folding and thrusting on a colossal scale, resulting in the Rocky Mountain system (Fig. 230*C*). The orogenic belt stretched from Alaska to Mexico. It involved a region fully 3000 miles long, and in the United States it had a maximum

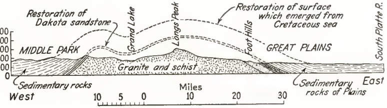


FIG. 231. Section across the Front Range near Denver, showing its arched structure and suggesting the amount of erosion that has occurred since the uplift began. After W. T. Lee, U. S. Geological Survey.

width of 500 miles, extending from eastern Colorado to eastern Nevada and central Idaho. It was clearly the most far-flung orogeny that North America had experienced since Pre-Cambrian time, and deserves to rank as one of the great revolutions. It was long ago named the *Laramide revolution,* after the Laramie Range in Wyoming.

Nature and Extent of the Disturbance. Although the region has since suffered much erosion and has gone through a Late Cenozoic revolution, the Cretaceous structures are still as a rule clearly shown, and we can reconstruct the Late Cretaceous mountains in considerable detail.

The orogenic forces at work brought about a great regional compression from the west. The resultant structures differed greatly in diverse parts of the region, depending, undoubtedly, upon the nature and competency of the rocks involved, and, to some extent, upon the regional relation to the moving forces. Figures 231 and 232 will aid in presenting the results of the orogeny. (See also Fig. 267, p. 416.)

In the Southern Rockies the dominant structures were great open arches. The Front Range in Colorado and southern Wyoming is one of these, and another, lying parallel to it on the west, is represented

by the Park and Sawatch ranges. Between these lies a major synclinal fold still recognizable in the "Parks" (North, Middle, and South) of Colorado and in San Luis Valley. Farther northeast in the Plains were formed the domelike arches of the Black Hills and the Big Horns. West of the Colorado Rockies lay the great resistant mass of the Colorado Plateau, which remained almost undeformed. Between it and the Front Range were one or more great thrust faults, the best known lying along the front of the Sawatch Range.

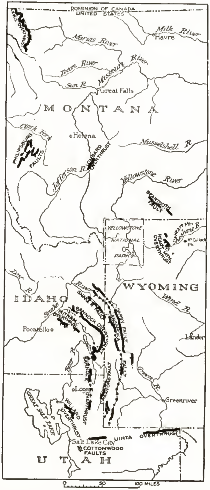


FIG. 232. Trace of the major thrust faults produced by the Laramide revolution in the Cordilleran region. After G. R. Mansfield, U. S. Geological Survey.

The Middle and Northern Rockies were involved in thrust faulting of great magnitude. The trace of the better known of these faults is shown in Fig. 232. The Lewis thrust along the front of the Montana Rockies is illustrated in Part I (p. 467). Here the thick Proterozoic strata were driven eastward many miles over the Cretaceous rocks of the Plains, on a fault that has been traced for more than 50 miles north and south and may be continuous with a similar great thrust west of Great Falls, 100 miles to the south. The east front of the Absaroka Range east of Yellowstone Park is defined by another fault, the Heart Mountain thrust, which is traceable for probably 125 to 150 miles and has an eastward displacement of at least 28 miles. Greater still is the Bannock thrust of southeastern Idaho, which has been traced for 250 miles and has carried Cambrian and Ordovician rocks up over those of Pennsylvanian and Triassic ages

in an eastward overthrust of at least 35 miles. This is but one of several great thrusts in southeastern Idaho, and others are known in northern Utah and especially in southern Nevada, where a series of low-angle faults, dipping westward, involve the Jurassic and older rocks in a region where Cretaceous sediments were not present.

West of this great belt of thrust faulting, the Cretaceous structures are now largely obscured by the Cenozoic formations in the Great Basin and the lavas of the Columbia River plateau. The entire Pacific coastal belt was also uplifted enough to be completely emergent, for there is a great stratigraphic break between the Eocene and the Cretaceous in that region, but such deformation as there was must have been of the nature of regional upwarping or faulting, rather than folding. Early in the Cenozoic those great structural troughs (remnants of the Pacific Coast geosyncline) now seen in the Gulf of California, the California trough, and Puget Sound began to take form as a result of normal faulting.

Fig. 233. Late Cretaceous batholiths. The large area is the Idaho batholith, and the area south of Helena is the Boulder batholith. Smaller intrusions are exposed about Butte.

Volcanism. Volcanoes were active intermittently on the old Mesocordilleran geanticline throughout the later Cretaceous, and toward the end of the period they spread farther east over the rising areas. There is much volcanic agglomerate in some of the uppermost Cretaceous beds near Denver which must have come from volcanoes in Colorado. In fact, it is probable that during the Laramide revolution every state west of the Great Plains had its active volcanoes.

During the crustal movements granitic batholiths were intruded in several regions. The most notable of these are the great *Idaho batholith* (Fig. 233), whose eroded summit is now exposed over an area of 16,000 square miles in central Idaho; and the *Boulder batholith,* which underlies the region between Butte and Helena, Montana, and in which the great copper deposits of Butte were formed somewhat later.

Date of the Laramide Orogeny. It must not be supposed that a revolution so vast and complex was accomplished in a short time, even geologically speaking, or that the movements were strictly synchronous in all parts of the Cordilleran region. Although the climax of the orogeny naturally determined the end of the Cretaceous period,

this was hardly a point in time but rather a phase in a great diastrophic cycle, and it came long after the uplift had begun. Meanwhile, the latest of the Cretaceous sediments were accumulating on the flanks of the rising mountains or in the intermont basins. Moreover, such great forces as those involved in the building of the Rockies were not all brought to rest at once.

As the moving forces accumulated, the sea floor buckled and local anticlinal folds arose as islands long before the sea had vanished. Evidence for this may be seen, for example, in southeastern Wyoming, where the Mesaverde formation of late (but not latest) Cretaceous age locally includes an erosion channel some 200 feet deep filled with sandstone and conglomerate, in which some of the boulders are of the Cloverly and Mowry formations that lie some thousands of feet lower in the section; and the Medicine Bow formation (very late Cretaceous) includes boulders of the Pre-Cambrian granite floor. These localities are almost in the center of the geosyncline; and since such coarse material could not have traveled far, it implies local uplift and deep erosion of the rising masses in the midst of the region of deposition.

In the critically studied Wasatch region to the northeast of Salt Lake City, eight stages of deformation have been recognized.[1] The first came at the close of the Jurassic or some time early in the Cretaceous and produced local highlands in western Utah. This is inferred from the character of the oldest Cretaceous formation of the Wasatch region, which begins with 700 feet of conglomerates. In these the boulders increase in coarseness and in abundance toward the west, and include fossiliferous pieces of Paleozoic formations that could only have been laid bare by uplift and deep erosion. This uplift may have been connected with the Nevadian rather than the Laramide disturbance.

A second and major disturbance, in the midst of Late Cretaceous time, resulted in east-west folds where the Uinta range later developed. Erosion of these folds truncated some 25,000 feet of beds which were unconformably covered by later Cretaceous deposits (the Henefer formation). This deposition continued to the end of the Cretaceous (possibly early Paleocene) and was followed by the climax of deformation that produced large-scale thrust faulting (Willard thrust). Sharp local folding occurred during Middle Paleocene time, and more gentle warping followed the Lower Eocene and was repeated in the Oligocene epoch.

Movement continued along some of the great thrust faults until long after the beginning of the Cenozoic, dying out in the Eocene or possibly in the early Oligocene. Just as the movements began earlier in some regions than in others, so also they continued longer in some of the ranges than in others. Likewise, the volcanism continued with irregularly decreasing vigor into the Cenozoic, and in many places it is not now possible, after extensive erosion, to distinguish clearly between Late Cretaceous and Early Cenozoic volcanics. The protracted nature of these orogenic movements still further complicates the difficult problem of fixing the boundary between the Mesozoic and Cenozoic rocks in the Cordilleran region. The problem is discussed on p. 375.

Late Cretaceous Orogeny in Other Continents

During both the Paleozoic and Mesozoic there existed along the western side of South America a great Andean geosyncline, which received thick sediments from a wide and repeatedly rising borderland to the west. During the last half of Cretaceous time this geosyncline was folding and rising into a great mountain chain that was completed at the end of the Mesozoic. Beginning east of Trinidad, off Venezuela, these mountains extended southwestward into Colombia and thence southward to beyond Cape Horn, a distance of nearly 5000 miles. They were the South American counterpart of the Rocky Mountain system.

Standing athwart the course of the Rockies and the Andes is the Antillean mountain system of Central America, also formed at this time, following the trend of the Greater Antilles.

Stratigraphy of the Cretaceous Rocks

Atlantic Coastal Plain

Cretaceous formations underlie the Atlantic Coastal Plain from New Jersey southward and form a wide belt of outcrop where not overlapped by Cenozoic beds. They are mostly sands and clays, disposed in nearly flat-lying beds that dip very gently seaward. For the most part, they are only slightly indurated, the clays being soft and the sands loose and friable, but locally the sands are solid enough for building stone.

The entire system is less than 1000 feet thick in the outcrop belt, where it thins and laps out against the land. It thickens down dip and probably reaches its full thickness some distance off shore, as shown by a well drilled in 1946 at Cape Hatteras, approximately 100 miles east of the Cretaceous outcrops. This well reached the base of Cretaceous strata and penetrated granite at a depth of 9878 feet. Both Lower and Upper Cretaceous formations are in the marine facies at this locality.[2]

Lower Cretaceous formations are all nonmarine in outcrop, and exposures are practically limited to the Chesapeake Bay region and New Jersey. The shoreline was clearly farther east than the present outcrop belt. The Lower Cretaceous begins with basal sands that are coarse and gravelly, commonly arkosic, and generally cross-bedded. Sands and clays alternate and also grade laterally one into another. These features, along with the fossil land plants, crocodiles, and fragmentary dinosaur remains, indicate deposition by streams on a low coastal plain. Dark, lignite-bearing clays record local swamps, whereas brightly colored and variegated clays, such as those extensively exposed about Baltimore, were deposited on well-drained parts of the landscape.

Upper Cretaceous formations overlap and largely conceal the Lower Cretaceous south of Chesapeake Bay and form a wide belt of outcrop along the inner margin of the Coastal Plain most of the way from New Jersey to Georgia. They resemble the Lower Cretaceous formations in being detrital and relatively unconsolidated, but are for the most part marine. The higher formations include extensive deposits of "greensand marl," which is composed of sandlike granules of glauconite, a silicate mineral rich in potassium and iron. Before the discovery of rich potash salt deposits in the Permian of Germany, the New Jersey greensand was extensively quarried for the extraction of potassium used in the manufacture of fertilizer. Curiously, greensand, like chalk, is more abundant in Cretaceous rocks than in any other system, though by no means confined to them. The greatest deposits are in New Jersey, but much glauconite occurs farther south, even in the Gulf Coastal Plain. In the Lower Cretaceous of western Europe, also, glauconite is so common that a considerable series of these strata is commonly known as "The Greensand."

Eastern Gulf Region

From Georgia to northern Mississippi and western Kentucky the Upper Cretaceous overlaps on the Paleozoic and older rocks, covering

the Lower Cretaceous formations completely. Here the Upper Cretaceous attains a thickness of 2000 feet or more (Fig. 234). Although it begins with nonmarine sands (Tuscaloosa formation), it is largely a marine deposit, and in eastern Mississippi and western Alabama the upper 1000 feet is a soft, argillaceous limestone known as the "rotten limestone" or the *Selma chalk* (Fig. 235). Eastward, in Georgia, the limestone changes into shale and sands, and to the westward the "chalk" also becomes more muddy and grades over into a thick ma-

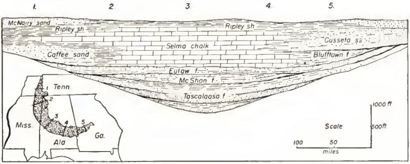


FIG. 234. Cross-section of the Upper Cretaceous formations of the eastern Gulf Coastal Plain, showing facies changes along the strike. As indicated by the inset, the section runs nearly south from western Tennessee to east-central Mississippi and then swings eastward to central Georgia. The central part was deposited farther from the Cretaceous shoreline than either end, and deposition began there first. Vertical scale greatly exaggerated. Adapted from L. W. Stephenson and from Watson H. Monroe, U. S. Geological Survey.

rine shale known as the *Ripley* (Fig. 236). Still more to the west and north, tongues of sand interfinger into the shale, and the formation grades laterally into the *McNairy sandstone,* which in places bears abundant fossil land plants.

In short, three types of sediment were forming simultaneously in the eastern Gulf region during later Cretaceous time: (1) sands and silt in western Tennessee and Kentucky (also in Arkansas), (2) silt and mud in northern Mississippi, and (3) calcareous mud farther south and east. Here is a parallel to modern conditions, wherein sand and mud are being laid down on the floor of the Gulf near the mouth of the Mississippi River, while fine mud spreads farther east and limestone is forming in the clear shallow waters about Florida. The McNairy sandstone represents part of a Cretaceous delta formed by streams foreshadowing the present Mississippi River system, and, since the sands spread more and more widely as we ascend in the

series, we may infer that the delta was growing southward toward the close of the period.

All of Florida now has Cenozoic strata at the surface, but deep wells indicate the presence of Upper Cretaceous formations resting on very ancient rocks. A recent deep well in western Florida (Jackson County) went through more than 4000 feet of Upper Cretaceous strata; and another, 50 miles west of Miami, near the southern tip of Florida, penetrated 2276 feet of Upper Cretaceous and 1900 feet of probable Lower Cretaceous, stopping in supposed Lower Cretaceous at a depth of 10,006 feet.

Western Gulf Border and the Cordilleran Region

Comanche Series. The Mexican sea gradually extended northward across Texas, depositing marine formations far and wide over the western Gulf border and in the Rocky Mountain trough. The Lower Cretaceous has a grand development in Texas and Mexico, with 4000 feet of richly fossiliferous limestones and marls in the latter country and about 1500 feet in southern Texas. These formations constitute the Comanche series, so named for the many outcrops in the ancestral home of the Comanche Indians. Nearly one-half of the vast domain of Texas is covered with either Lower or Upper Cretaceous forma-

L. W. STEPHENSON, U. S. GEOLOGICAL SURVEY.

Fig. 235. Typical exposure of the Selma chalk, Jones Bluff, Tombigbee River, Alabama.

tions, and the marine record is here the most complete in the United States. More than half of the mineral wealth of Texas (largely petroleum) is now produced from these rocks.

The Comanche formations are almost entirely limestone in eastern and central Mexico, but in Texas and Arkansas they grade over into a near-shore facies of calcareous shale, sandstone, and thin-bedded

Carl O. Dunbar.

FIG. 236. Outcrop of Ripley shale showing a shell "bank" made by *Gryphæa convexa*, a relative of the oyster. Near Corinth, Mississippi.

limestone. Only the uppermost beds were involved in the overlap across Kansas and Iowa, and there they are shales and sandstones, fluvial in part. It is significant also that detrital sediments thin out gradually in their overlap on the old lowland toward the north, whereas in southeastern Arizona (at Bisbee) they thicken to 4700 feet and include thick conglomerates and much sandstone.

The influence of the Mesocordilleran highland is evident here as well as in northwestern Mexico, where the Comanche formations are thick (3000 feet in northeastern Sonora), detrital, and coal-bearing.

There is another notable Lower Cretaceous development in the Rocky Mountain trough of Canada. The seaway responsible for these beds was an extension from the Arctic which began to invade Canada

T. S. LOVERING AND F. M. VAN TUYL, U. S. GEOLOGICAL SURVEY.

Fig. 237. East flank of the Front Range near Denver, showing hogbacks of Cretaceous and older strata uparched by the Laramide revolution. An aerial view looking north, from an altitude of 7100 feet. The great hogback in the foreground is formed of Dakota sandstone, and those in the middle distance at the left are of Pennsylvanian (Fountain) sandstone. The mountains at the left are of Pre-Cambrian granite. Longs Peak is at the horizon just left of the center of the view.

in the middle of Early Cretaceous time, and finally, early in the Late Cretaceous, united with the transgressing waters from Mexico. In southern Alberta the Lower Cretaceous formations are largely of fresh-water origin (Kootenai and Blairmore), but those of the Upper Cretaceous are largely marine.

Upper Cretaceous Series. The Upper Cretaceous formations underlie all the Great Plains and much of the Rocky Mountain region, generally exceeding 2000 feet in thickness in the east and attaining a maximum in western Wyoming of about 20,000 feet. Their stratigraphic relations are complicated by the facts that the sediments were coming largely from the western highlands, and that from time to time vast deltas or alluvial coastal plains were developed along this side of the trough, while finer-grained marine sediments were accumulating farther east across the geosyncline. This resulted in an interfingering into the marine section of great wedges of continental deposits from the west, bearing the remains of land

plants, coal beds, and dinosaurs (Figs. 238, 239). Hence the lithologic characters and the divisions recognized in one area do not agree with those of another, and only the larger groupings can be presented here. In general, however, four great divisions are recognizable, the Dakota sandstone, the Colorado group, the Montana group, and the Laramie group.

The *Dakota sandstone* is the basal member of the Upper Cretaceous over a very large area. Although generally between 100 and 400 feet thick, it persists under most of the Great Plains and outcrops in strong

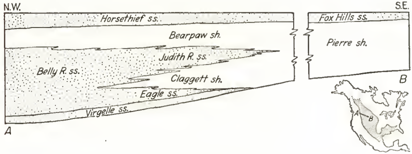


FIG. 238. Idealized cross-section of the Montana group of the Upper Cretaceous system, from southern Alberta (*A*) to the Black Hills of South Dakota (*B*), showing the interfingering of the marine shales (*unshaded*) with tongues of sandstone (*stippled*) from the west. The Virgelle, Horsethief, and Fox Hills sandstones are shallow-water marine deposits, but the Belly River-Judith River beds are floodplain and delta deposits, bearing land plants and dinosaurs. Length of section 700 miles, a considerable length of the middle part being deleted. Adapted from E. Stebinger, U. S. Geological Survey.

hogbacks (Fig. 237) along the front of the Rockies and about the Black Hills. It is the chief horizon for artesian water in the eastern Great Plains and is one of the greatest water reservoirs known. The Dakota sands are rusty, irregularly bedded, and generally cross-laminated; they include much silty shale and grade laterally from thick sand beds to shale in an irregular fashion. No marine fossils are present, but leaves of land plants are locally abundant. The formation was evidently spread over the floor of the geosyncline by aggrading streams in advance of the seas that were transgressing from both the south and the north.

The *Colorado group* (Figs. 230*B*, 239) includes fine-grained marine strata under the Great Plains, the lower part being dark gray shales (*Benton*) and the upper part a soft argillaceous limestone known as the *Niobrara chalk*. The chalk is of interest as the source of many striking vertebrate fossils, notably the large diving birds, the great

marine reptiles and fishes, and the greatest of all pterosaurs. Traced westward through Colorado and New Mexico, the limestone passes into shale, which in many places becomes sandy. Finally, in the Black Mesa coal fields of northeastern Arizona, the upper half of the group has gone over into massive cliff-forming sandstones with important coal beds.

The *Montana group* is rather simple in the central and eastern Great Plains, where it consists of a thick but very fine-grained marine shale (*Pierre*), capped by a shallow-water marine sandstone (*Fox Hills*). Northwestward, however, the marine shale is divided by

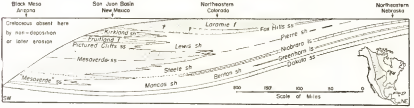


FIG. 239. Restored section of the Upper Cretaceous formations of the Rocky Mountain geosyncline, showing the intertonguing of thick nonmarine sandstones from the west (*stippled*) into the marine deposits. Vertical scale greatly exaggerated.

wedges of nonmarine sandstone and shale that thicken steadily toward the old shoreline at the expense of the marine shales. These are dinosaur- and coal-bearing deposits, representing deltas or coastal plains formed in front of the rising land mass of the Mesocordilleran geanticline (Fig. 238).

The *Laramie group* includes several thousand feet of nonmarine coarse detritals spread over the floor of the geosyncline by aggrading streams after the sea had withdrawn. It was named for the Laramie basin in Wyoming, where it is very thick, as it likewise is in the Denver basin of Colorado, the Big Horn basin of Wyoming, and the western part of the plains of Wyoming and Dakota, but it thins gradually toward the east in the Dakotas. There is also a large area of these deposits in the plains of Alberta.

Fossil land plants are abundant, and the last of the dinosaurs are represented by many fine skeletons, but no marine fossils are present.

The Laramie group has given rise to one of the two most prolonged controversies in the history of American geology. The land plants are remarkably modern in their aspect and were believed by the early paleobotanists to be of Cenozoic age. The dinosaurs, on the contrary, are clearly allied with Cretaceous types and are quite unknown any-

where in undoubted Cenozoic rocks. Not a bone of any dinosaur has been found in the overlying Fort Union formation. Accordingly, some paleobotanists wished to draw the Mesozoic-Cenozoic boundary line *below* the Laramie, and the vertebrate paleontologists placed it *above* (some, even above the Fort Union). As the controversy became more acute, structural evidence was sought, but unfortunately, in the area where fossil vertebrates are common, no clear angular discordance is known between the youngest undoubted Cretaceous beds and those that are clearly Cenozoic. Erosional unconformities were found both below and above the Laramie (and in the Fort Union as well) in various localities, but such unconformities occur at many horizons in the nonmarine beds of the region, and the time significance of any particular one is problematical.

Closely allied in nature to the Laramie, and overlying it, is the Fort Union formation of fluvial sandstones and shales with abundant land plants, many mammal bones, and coals. Its plants have close affinities with those of the Laramie, but it has not a trace of a dinosaur. Restudy of the fossil plants of both Laramie and Fort Union strata has recently proved that they are really quite distinct, much of the older confusion having resulted from the mixing of Fort Union and Laramie collections because the stratigraphic boundary was not correctly understood.[3] The evidence of fossil plants therefore now agrees with that of the vertebrates as to the Cretaceous-Cenozoic boundary.

Beds identified as Fort Union strata in the Big Horn basin have recently yielded four distinct zones of mammalian fossils which show a definite correlation with the oldest Cenozoic (Paleocene) formations. The details are presented in Chapter 17.

California and British Columbia

As portions of California subsided after the Nevadian disturbance at the close of the Jurassic, coarse detrital sediments from the mountains poured into the basins and accumulated rapidly and to great depths. The Lower Cretaceous strata, known as the *Horsetown formation,* commonly reach a thickness of 10,000 feet and at a maximum exceed 26,000 feet along the west side of the Sacramento Valley in California. Recently the volume of the detrital Cretaceous deposits (mostly Lower Cretaceous) in that valley has been estimated at 13,400 cubic miles. Fossils are sparse, and the material is partly of brackish- or fresh-water deposition, but marine fossils are scattered through the section and five distinct faunal zones prove that all the major divisions of Lower Cretaceous time are represented.

The early half of the Late Cretaceous is represented in California by the *Chico formation* of sandstones, shales, and conglomerates, having a thickness of several thousands of feet. The same formation is thick and coarse all along the coastal belt of British Columbia from Alaska to Vancouver Island, measuring 5000 feet thick at the latter place and 11,000 feet in the Queen Charlotte Islands, where there is much volcanic material.

Mineral Resources

Coal. In the Late Cretaceous and Early Cenozoic (Fort Union) rocks of the Rocky Mountain region, there are more than 100,000 square miles of coal-bearing lands (Fig. 240). These fields have an estimated reserve of almost 900,000,000,000 tons in beds more than a foot thick and within 3000 feet of the surface. However, most of this coal is of low rank (either bituminous or sub-bituminous) and does not now compete to any considerable extent with the older coals outside the Rocky Mountain region. Locally, where the metamorphism is severe or where igneous rocks have invaded the Coal Measures, as in the Crested Butte field of central Colorado, anthracite is mined.

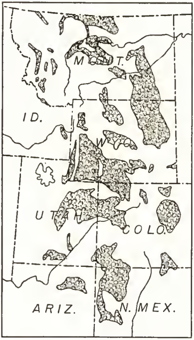


Fig. 240. Cretaceous and early Cenozoic coal fields of the Rocky Mountain region. After M. R. Campbell, U. S. Geological Survey.

This coal varies in age from field to field. In the Black Mesa field of northeastern Arizona it is in the basal part of the Upper Cretaceous, but by far the greatest part is in the Laramie group at the top of the Cretaceous and in the Fort Union at the base of the Cenozoic. Considering the region as a whole, the Fort Union is probably the greatest coal-bearing horizon. In the Anthracite-Crested Butte fields of Colorado, the coal is of Laramie age.

Colorado is now the leading coal producer among the western states, but Wyoming appears to have far greater reserves. In the Crowsnest

Pass region of Alberta, there are extensive coals in the Lower Cretaceous (Kootenai) strata, and where these rocks have been severely folded it is estimated that some 400,000,000 tons of the coal are anthracite.

Petroleum. Cretaceous rocks have been an important source of oil and gas in several parts of America. They are the chief horizon of the Mexican oil fields and for many years kept that country in the forefront as one of the three greatest oil producers in the world. Phenomenal gushers like Cerro Azul No. 4 in the Huasteca field, which jetted 1,000,000 barrels during its first week of flow, seem to have derived their oil from caverns in the Lower or Middle Cretaceous limestones. Venezuela has also produced much oil from the Cretaceous, and Argentina a smaller amount. In the United States, Cretaceous production supplies the great Salt Creek field of Wyoming and many others in that state, Montana, and Colorado. The richest of all the North American fields was brought in during 1930 in the Cretaceous rocks of eastern Texas, where an old beach deposit of the overlapping Upper Cretaceous was found to be saturated with oil over an area 4½ miles wide and 38 miles long. The extraordinary yield from this area led to the overproduction of 1931–1932, which was followed by enforced curtailment of the oil output in Oklahoma and Texas.

Gold, Silver, and Other Metals. Metalliferous deposits were formed widely throughout the Rocky Mountain region as a by-product of the igneous activity that accompanied the Laramide revolution. The copper, zinc, and silver veins of Butte, Montana, the most richly mineralized district in the world, were formed at this time. Mineralization has recurred at different epochs in different mining regions during the late Cenozoic, so that it is impossible at present to generalize and say how much of the mineral wealth of America should be attributed to the late Cretaceous events, but the gross value must be very great.

Climate

The general temperature seems to have fallen somewhat after the Nevadian disturbance, for reef corals were more restricted in the Early Cretaceous than they had been in the Jurassic. Moreover, in the middle part of the Early Cretaceous (Aptian time) the highland plateau of eastern Australia appears to have been ice-capped, with glaciers flowing westward into the sea. In any event, icebergs dropped into the interior sea well-striated stones in sizes ranging up to 6 feet

across, and these erratics are known through some 600 miles of outcrops.[4]

With the greater spread of the seas in early Late Cretaceous time, the climate gradually became mild and equable over most of the land surface of the Earth, especially during the latter part of the period. Upper Cretaceous rocks preserve, even in high latitudes, abundant remains of land plants belonging to genera now restricted to warm-temperate or subtropical regions. In central-western Greenland, for example, the Cretaceous beds contain figs, breadfruits, cinnamons, laurels, and tree ferns, and in Alaska they have yielded cycads, palms, and figs. Although most of these are commonly thought of as strictly tropical trees, each of the genera has representatives in the temperate zone, and it is not necessary to conclude, as some have done, that tropical climate extended into polar latitudes. Nevertheless, there is sufficient evidence for maintaining that Greenland was without an ice cap and that the climate there was then temperate rather than frigid.

The abundance of the great dinosaurs in Alberta and Mongolia during part of the Cretaceous seems to imply a very mild temperate climate at least that far north.

There was apparently a marked drop in the temperature of western North America after the Laramide revolution, however, for extensive mountain glaciers existed in the San Juan Mountains of southwestern Colorado in early Cenozoic time. This may have been an important factor in the extermination of the dinosaurs and other characteristic groups of Cretaceous land animals.

Life of Cretaceous Time

Spread of Modern Plants

Deciduous trees suddenly became conspicuous in the Early Cretaceous, and long before the close of the period dominated the landscape in all the continents, just as they do today. Among the oldest of these were the magnolia, fig, sassafras, and poplar, all of which appear in the middle Lower Cretaceous deposits. By the middle of the period the forests were essentially modern, including such trees as beeches, birches, maples, oaks, walnuts, planes, tulip trees, sweet gums, breadfruit, and ebony, along with shrubs like the laurel, ivy, hazelnut, and holly (Fig. 241).

With these, of course, there were evergreens, just as now, but they no longer dominated the landscapes as they had done during the earlier Mesozoic. Among the conifers a conspicuous type was the sequoia;

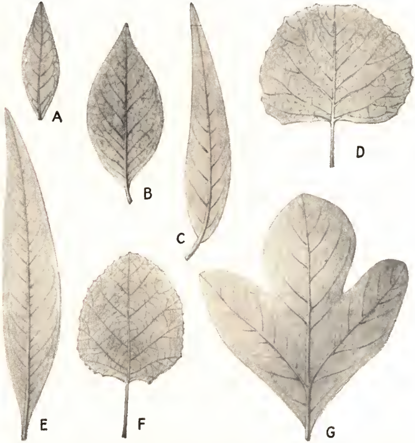


FIG. 241. Cretaceous plants. *A*, *Andromeda snowi*, a relative of the rhododendrons; *B*, *Magnolia pseudoacuminata; C*, *Salix lesquereuxi*, a willow; *D*, *Populites elegans*; *E*, *Ficus lanceolata-acuminata*, a fig; *F*, *Betulites westi latifolius*, a birch; *G*, *Sassafras parvifolium*, a sassafras. After E. W. Berry and L. F. Ward.

although none are known so large as the modern giants of California, it is interesting to note that the race was widely distributed over the northern hemisphere at this time.

Most deciduous trees belong to the *angiosperms*, the highest order of the plant kingdom and the one that includes all the true flowering

plants (exceptions are certain gymnosperms, such as the gingko and the larches). Besides the hardwood trees mentioned above, this order includes the grasses and cereals as well as the seed- and fruit-bearing shrubs, annuals, and our common vegetables. The strong deployment of this group of plants in the Cretaceous was one of the most significant advances in the whole evolution of plant life, second only to the spread of plants over the lands. On their own account, this was an important milestone in the history of life, for the angiosperms are the most highly specialized of all plants and the ones destined to dominate the Earth during later geologic time. In addition, their indirect effect upon the advances of the higher animals can hardly be exaggerated, for they supply nearly all the plant food for the mammals that now dominate all other life upon the Earth. Angiosperms provide the nuts and fruits of the forest, the grasses of the prairies, the cereals which furnish fodder and grain for man and his domestic animals, and all the vegetables and fruits that man has cultivated, to say nothing of the flowers that add so much pleasure and inspiration to human surroundings. It would hardly be too much to say that the great expansion of the mammals and the birds had to wait upon the evolution of the flowering plants; it was certainly no accident that in the next period the reptilian hordes gave way to a spectacular rise of warm-blooded vertebrates.

The oldest known angiosperms appear almost simultaneously in New Zealand, in Texas, and in the coastal plain of Maryland. Of these the best-known occurrence was described from the Paluxy sand of the basal Cretaceous Trinity group in Erath County, central Texas.[5] Three types of deciduous tree leaves were found, one of which is a species of cinnamon. From middle Lower Cretaceous rocks angiosperms are known in Portugal and Maryland. The oldest Cretaceous formation of the Atlantic Coastal Plain (Patuxent) has yielded none of these modern plants, though it has plenty of evergreens like the Jurassic floras. In the middle member (Arundel) of the Lower Cretaceous of Maryland, however, several species of deciduous trees are represented. Before the middle of the period they had spread over the Rocky Mountain region, and they comprise more than 90 per cent of the known plants of the Upper Cretaceous.

The resting stage represented by the ripening of the seeds and the shedding of the foliage of angiosperms is clearly an adaptation to seasonal and rigorous climates, either of winter cold or of drought. Probably the evolution of these plants out of the older types took place on the highlands where the climate was cool and growth was

American Museum of Natural History.

FIG. 242. Skull of *Tyrannosaurus rex*, the greatest known carnivorous dinosaur. Length of original, 4 feet, 3 inches.

AMERICAN MUSEUM OF NATURAL HISTORY.

Fig. 243. Tyrannosaurus rex and Triceratops horridus, from a painting by C. R. Knight. Based on specimens from Hell Creek basin, Montana.

seasonal, but, if so, it was not until they had migrated into the lowlands where sedimentary deposits were forming that they left a record of their existence. It is quite possible, therefore, that they were actually present in Jurassic or Triassic time even though our oldest record is in Cretaceous rocks.

Culmination of Reptilian Evolution

Dinosaurs held the center of the stage until the last scene of the Mesozoic drama (Frontispiece). The great sauropods persisted locally where the environment was suitable, as proved by recent finds in the Lower Cretaceous of Wyoming and in the Upper Cretaceous of New Mexico, Utah, and Texas. They are known also from very fragmentary remains in the Cretaceous rocks of Maryland and South America. *Stegosaurus* was extinct, but its race persisted in heavily plated types like *Palæoscincus*. The two great races of bipeds, however, were at their climax. The carnivores varied much in size. Among them stalked *Tyrannosaurus rex*, the mightiest flesh-eater ever

AMERICAN MUSEUM OF NATURAL HISTORY.

Fig. 244. The duck-billed dinosaur, Trachodon mirabilis, *from Converse County, Wyoming. Painted by Charles R. Knight. Such animals were about 25 feet long from nose to tip of tail.*

present upon the lands, carrying his ponderous head 20 feet from the ground and spanning about 45 feet from nose to tip of tail (Frontispiece; Figs. 242, 243). In striking contrast with this "king tyrant saurian" there were other carnivores of small stature (*Ornithomimus*) which had no teeth but only a horny beak much resembling that of an

C. W. Gilmore, U. S. National Museum.

FIG. 245. Portion of the tail of a late Cretaceous bipedal dinosaur, *Corythosaurus*, with part of the skin preserved. Red Deer River Valley, Alberta.

ostrich. They probably fed like an ostrich and therefore were not truly carnivorous, though descended from flesh-eating ancestors. The herbivorous bipeds were well represented by the "duckbills" in Late Cretaceous time (Figs. 244, 245). Besides these, a fifth great tribe, the *Ceratopsia* or horned dinosaurs (Frontispiece; Figs. 243, 246), now made their appearance. The only occurrence of ceratopsians outside of North America is that of *Protoceratops* in Mongolia, where skeletons representing all stages of growth have been found, with several nests of eggs (Figs. 246, 247). This was a small form with a height of only 3 or 4 feet. In the Late Cretaceous some of the American Ceratopsia were 20 feet long and more than twice as bulky as the

Chicago Natural History Museum.

Fig. 246. The primitive horned dinosaur, *Protoceratops*, with nest of eggs. Painting by Charles R. Knight, based upon skeletons and nests from the Gobi Desert of Mongolia. This species attained a length of only 8 or 10 feet.

American Museum of Natural History.

Fig. 247. Dinosaur nest with broken eggs weathering from the rock. The eggs are about 4½ inches long and are believed to be those of *Protoceratops*. Djadochta beds, Gobi Desert, Mongolia.

greatest living rhinoceros. Pieces of dinosaurian eggshells have also been found at the top of the Cretaceous (Lance) near Red Lodge, Montana.[6] The duckbills and the horned dinosaurs outlived the others and are common fossils in parts of the Laramie group (especially the Lance beds).

Curiously, no dinosaurs were known in the far western Cretaceous until 1936, when abundant bones of a trachodont were found near Patterson, California.

Fig. 248. A mosasaur, *Clidastes*, from the Niobrara chalk in Kansas. After S. W. Williston. The animal was 12 to 15 feet long.

Reptiles of the Sea. Ichthyosaurs passed their heyday before the close of the Jurassic and were unimportant in the Cretaceous seas. On the other hand, the clumsy *plesiosaurs,* though less numerous than before, attained their greatest size. One species of these (*Elasmosaurus*), found well preserved in the Niobrara chalk of Kansas, reached a length of 40 to 50 feet, of which about half consisted of a very slender, agile neck. The dominant group of marine reptiles was a newly evolved tribe, the *mosasaurs* (Fig. 248), which made its appearance at this time. At first sight mosasaurs might be mistaken for ichthyosaurs, but there are four obvious points of difference which prove that they represent a wholly distinct order of reptiles, more closely related to the lizards and snakes than to the ichthyosaurs. First, they had scaly skins like a snake. Second, the lower jaw had extra joints, one at the chin and one near the middle of each side, which permitted the mouth to widen as it gaped (exactly as in a snake) so that very large animals could be swallowed. Third, the limbs were less specialized than those of ichthyosaurs, being simple five-fingered flippers. Finally, the tail flukes were quite differently shaped. The mosasaurs were obviously rapacious carnivores and the most ruthless pirates of the Mesozoic seas. The largest reached a length of about 35 feet. Marine *turtles* were present, and one specimen of phenomenal size (*Archelon*) has been found in the Pierre shale of Wyoming, measuring 11 feet in length

U. S. NATIONAL MUSEUM.

Fig. 249. Pteranodon, the greatest of the pterosaurs. A reconstruction made under the direction of S. P. Langley, pioneer in aviation studies. The wing spread of this pterosaur was between 23 and 25 feet

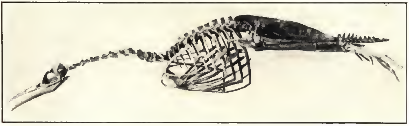
and 12 feet across the flippers. In the rivers both broad-nosed and narrow-snouted crocodiles were common.

Last of the Winged Dragons. *Pterosaurs,* though less varied and numerous than before, were large and remarkably specialized. The largest known form, *Pteranodon,* had an extraordinary wing spread of 23 to 25 feet, thus greatly exceeding any other winged creature of all time. Even so, the body was not larger than that of a wild goose, and with its delicate hollow bones the creature must have been almost as light and fragile as a kite. The remains of *Pteranodon* are found in the Niobrara chalk in Kansas far from the Cretaceous shoreline (Fig. 249), and it was clearly adapted to soaring over the waves like the modern albatross. In fact, this great reptile would have been quite helpless on the ground, for the hind limbs were so small and degenerate that they probably could not have borne even its light weight. Everything had been sacrificed to the achievement of sustained flight.

Unlike the Jurassic pterosaurs, the known Cretaceous species were toothless, their horny beaks displaying a remarkable parallelism with those of the post-Mesozoic birds.

Birds with Teeth

With one exception, all the birds yet discovered in Mesozoic rocks had teeth. Aside from the three Jurassic specimens, these are all from the Cretaceous. The greatest number of specimens have come from the Niobrara chalk of Kansas. Two very distinct types of birds are known, both obviously adapted to marine life. The one was a small shore bird with powerful wings (*Ichthyornis*), known only from two unique specimens at Yale; the other is the large diving bird, *Hesperornis* (Fig. 250), of which many skeletons have been found and sev-



Yale Peabody Museum.

Fig. 250. The great diving bird, *Hesperornis regalis*, from the Niobrara chalk of Kansas, mounted in diving posture. Note the long tail and vestigial wings. Over-all length about 4½ feet.

eral have been articulated and mounted in lifelike position. This remarkable bird, like the living penguin, was so perfectly adapted to life in the water that it had lost the power to fly and had only internal vestiges of wings. It reached a length of nearly 6 feet, standing about 4½ feet high (if, indeed, it could stand at all). Its long slender jaws were armed with pointed, conical, but recurved teeth, well adapted to capturing and holding slippery fishes and perhaps squids. The tail was several inches long but not nearly so long as that of *Archæopteryx*.

It is obvious that these two highly specialized marine types do not fairly represent the bird faunas of the time. Recently a well-preserved lower jaw of a toothless bird was found in nonmarine strata of Late Cretaceous age in the Red Deer Valley of Alberta. Otherwise, toothless and land-dwelling birds are still unknown in the Cretaceous, but this is not surprising, since bird bones, besides being small and fragile, are hollow and air-filled, and easily destroyed. Even in near-recent deposits birds are generally the rarest of fossils.

Mammals Bide Their Time

So long as the dinosaurs held their own, and the grasses, cereals, and fruits had not become generally distributed, the primitive mammals could only bide their time. Thus far, almost all the known Cretaceous mammals come from the Laramie group and its equivalents at the top of the system. Among these the *multituberculates* persist, but the other three Jurassic orders are missing and presumably were extinct. However, two new orders now made their appearance, having evolved out of the Jurassic *pantotheres* before the demise of the latter. These new stocks were the *marsupials* (pouch-bearers like the opossum) and the *insectivores* (Fig. 251) (primitive placental mammals

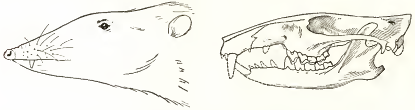


FIG. 251. A Cretaceous insectivore, *Zalambdalestes lechei*, from Mongolia. Flesh restoration (left) and composite reconstruction of skull (right), after G. G. Simpson. Natural size.

of the group to which modern shrews and moles belong). Some of the Cretaceous marsupials were remarkably similar to the modern opossum.

Modernization of the Invertebrates

By Cretaceous time the evolution of most of the invertebrate tribes had been practically accomplished, and nothing but details (genera and species) were left for the Cenozoic era. Only the *ammonites* and *belemnites* gave the marine faunas a medieval aspect. Both were on a decline numerically, though the ammonites still played a conspicuous role until the final ebb of the Montanan sea. Many species forsook their symmetrical plan of coiling, and developed bizarre shapes; some became spiral, like a snail's shell, a few straightened, many became loosely coiled, and a few lost all semblance of regularity or symmetry (Pl. 16). The significance of this extraordinary development in a decadent race is not fully understood. In the figurative language of Barrell, "they seem to have been writhing in the death agony of their race." In any event, not a single species lived past the end of the Cretaceous.

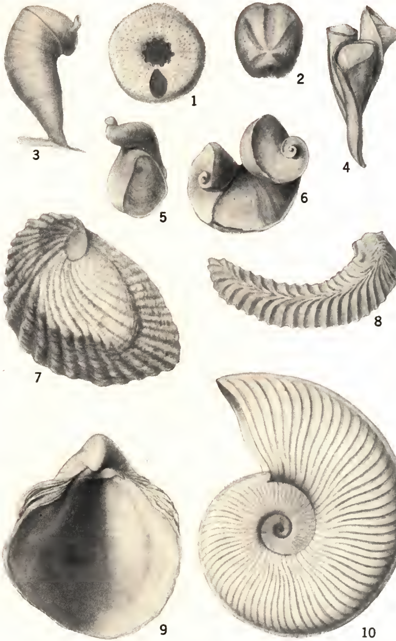


Plate 15. Lower Cretaceous Echinoids (1, 2), Clams (3–9), and Ammonite (10).

Fig. 1, *Holectypus planatus;* 2, *Enallaster texanus;* 3, *Monopleura pinguiscula;* 4, *M. marcida* (a cluster of three); 5, *Exogyra arietina;* 6, *Toucasia patagiata;* 7, *Exogyra texana;* 8, *Alectryonia* cf. *A. carinata;* 9, *Gryphæa tucumcari* (inner view of larger valve); 10, *Oxytropidoceras acutocarinatum.* All natural size. Drawn by L. S. Douglass.

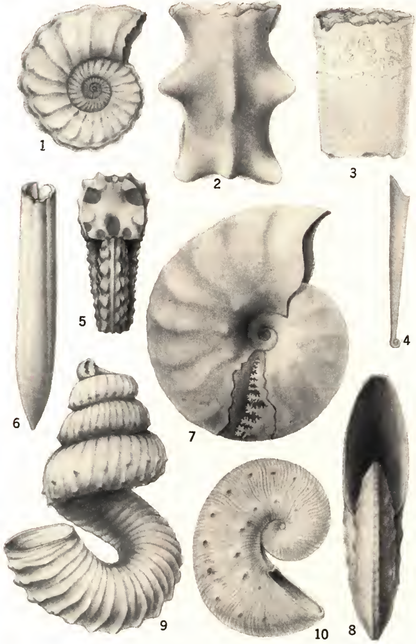


Plate 16. Upper Cretaceous Cephalopods.

Figs. 1, 2, *Prionotropis woolgari* (young shell and ventral view of fragment of large shell); 3, 4, *Baculites compressus*, a straightened ammonite (a juvenile shell, ×3, showing initial coiled stage; and a section from an adult shell showing sutures); 5, *Mortoniceras texanum* (edge view of a shell with living chamber broken away revealing last septum); 6, *Belemnitella americana*, one of the last of the belemnites; 7, 8, *Placenticeras lenticulare*, lateral and edge views; 9, *Heteroceras* sp., an ammonite irregularly coiling at maturity; 10, *Scaphites nodosus*. All natural size, except Fig. 3. Drawn by L. S. Douglass.

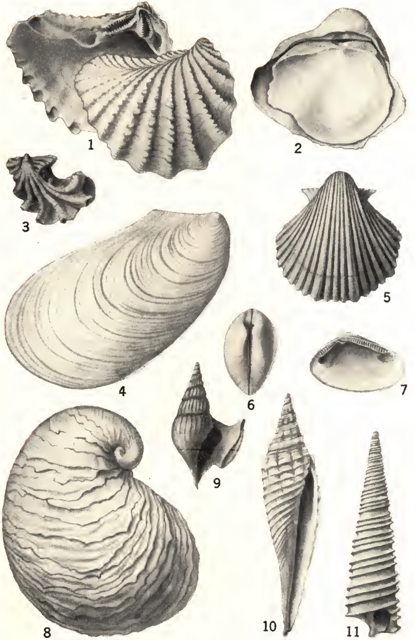


Plate 17. Upper Cretaceous Pelecypods (1–8) and Gastropods (9–11).

Fig. 1, *Trigonia thoracica* (valves parted to show interior); 2, *Gryphæa convexa* (showing unequal valves); 3, *Alectryonia placenta* (a ribbed oyster); 4, *Inoceramus labiatus;* 5, *Pecten* (*Neithea*) *quinquecostata;* 6, 7, *Nucula percrassa* (dorsal view and interior of right valve); 8, *Exogyra ponderosa* (×⅓), an oyster-like clam with spirally twisted beak; 9, *Anchura lobata;* 10, *Volutoderma appressa;* 11, *Turritella trilira.* All natural size, except Fig. 8. Drawn by L. S. Douglass.

Clams (Pl. 15, figs. 3–9; Pl. 17, figs. 4–8) and *gastropods* (Pl. 17, figs. 9–11) of many kinds and of essentially modern appearance were abundant, but there was also a remarkable development of sessile, reef-making clams (*chamids*, Pl. 15, figs. 3, 4, 6, and *rudistids*) that gave a distinctive element to many of the Cretaceous faunas. Several of these were attached by the beak of one valve. This valve then grew up into a deep conical shell while the opposite valve served as an operculum. Many of these shells resemble corals and, like the latter, they contributed actively to the reefs in the Cretaceous seas. One form in Jamaica grew 5 feet tall. *Oysters* (Pl. 15, figs. 8–9; Pl. 17, fig. 3) were very common, and two related stocks, the Exogyras and Gryphæas, are among the most distinctive invertebrates of this time.

Brachiopods were no more common than they are today, and are abundant only locally in Cretaceous rocks. Corals were plentiful in Europe but not in America. Siliceous sponges also were important reef makers in Europe but are seldom seen here. The *heart-urchins* are particularly common in the Comanche series of Texas and in the Upper Cretaceous of Europe. *Crabs* were common in the sandy sublittoral zone, then as now.

Insects are not common fossils simply because suitable deposits have not been found, but it is fairly certain that all the chief modern types were already represented. Probably early in the Cretaceous the insects adapted themselves to feeding upon the nectar of the newly arisen flowering plants and thus gradually assumed their important role in pollenization. One of the most remarkable recent discoveries is a fossil wasp nest from the Upper Cretaceous of Utah.

Close of the Period: "The Time of the Great Dying"

The end of the Cretaceous, like the close of the Paleozoic, proved to be a great crisis in the history of life. Several stocks of animals declined markedly *during* the period; others flourished till near its end only to become extinct. For example, the dinosaurs were highly varied and apparently adaptive right up to the end of Laramie time, yet not one is known to have lived to see the dawn of the Cenozoic era. The pterosaurs specialized perhaps too far, attaining their greatest size only to die out considerably before the close of the period. Among the great marine reptiles, the ichthyosaurs and plesiosaurs were already on a marked decline, while the mosasaurs underwent a meteoric evolution, yet all these died out and only the marine turtles sur-

vived. The decline and extinction of the ammonites and belemnites at the very close of the period, and the passing of the several stocks of reef-forming clams (rudistids) show that the marine invertebrates did not escape the crisis.

It is difficult to account for the simultaneous extinction of great tribes of animals so diverse in relationships and in habits of life. Perhaps no single cause was responsible. The great restriction and final disappearance of the epeiric seas at the end of the era, the rise of highlands from Alaska to Patagonia, a sharp drop in the temperature accompanying the Laramide uplift, the vanishing of the swampy lowlands, and the vastly changed plant world have all been invoked to account for the extinction, and the consequent rising of the weak and lowly into new kingdoms. Whatever the cause, the latest Mesozoic was a time of trial when many of the hosts were "tried in the balance and found wanting"—wanting in adaptiveness to the new environment. Walther has picturesquely called it "The time of the great dying."

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V. THE MODERN WORLD UNFOLDS

CHAPTER 17

PHYSICAL HISTORY OF THE CENOZOIC ERA

General Features. Every feature of the modern landscape was shaped during the last short era of geologic time. The Alps and the Himalayas have come up from the sea floor; the Rocky Mountains have been worn down and then uplifted to their present height; the Appalachian ridges have been etched into relief; and all the other mountain ranges of the world have been elevated and sculptured to their present form since the beginning of the Cenozoic era. The streams also have attained the courses they now follow, and climatic zones have assumed their modern character. During this time also, the mammals evolved from unimpressive Mesozoic forebears to culminate in man. This era saw the modern world unfold!

It was a time of crustal unrest, lying between the Laramide revolution and the Cascadian-Alpine revolution from which we are just emerging. Movements still continue in many parts of the world where active volcanoes and violent earthquakes mark mobile zones still "alive." The climax of the disturbance is but recently past, if, indeed, we have seen its culmination, and the Earth is now in a rather exceptional stage of its history, the continents being abnormally large and emergent, the highlands more extensive and the mountains more lofty than normal, and the climatic zones more strongly diversified. For this reason the landscape is more varied, the scenic features grander, and the Earth as a whole more interesting than it has been during much of the geologic past. Since every surface detail can be traced to Cenozoic history, no other part of the geologic record has such a direct appeal.

The Cenozoic was the shortest of the eras, embracing but a single period of time, probably not exceeding 70 million years. The Mesozoic era was at least twice as long, and the Paleozoic five or six times as long. In this striking fact there is food for thought. The great

diastrophic movements during the last 500 million years, at least, have come at shorter and shorter intervals. Does this presage a time when the continents will stand still higher or be permanently emergent, and epeiric seas like those of the past will vanish for good, or will the pendulum swing back? The problem is too vast and our data are too few as yet to justify a positive belief.

History of Subdivision. The first attempt to subdivide the geologic record and establish a chronology goes back to the year 1759 and to Giovanni Arduino, a professor at the University of Padua. He had studied the southern Alps and the plains of Italy and recognized there four divisions of the Earth's crust formed one after another. These were: (1) the core of the mountains formed of crystalline rocks (plutonic and metamorphic); (2) the flanks of the mountains formed of limestone and marble, commonly fossiliferous and steeply dipping or strongly folded; (3) foothills composed of gravels, sands, and marls, and including the volcanics such as those about Vesuvius; and (4) alluvial material over the surface.

Arduino called the crystalline rocks *Primary,* because they were obviously the first formed of this series; the deformed and well-indurated strata of the mountain flanks he called *Secondary;* and the unconsolidated sediments of the Italian plain he named *Tertiary.* A fourth division, *Quaternary*, was added about the year 1830 to include the glacial, fluvial, and lake deposits that cover much of western Europe and that were originally thought to be the deposits left by the Biblical flood.

Arduino's scheme of subdivision, based on the degree of metamorphism, the structure, and the degree of induration of the rocks, was natural for the region he knew. Unfortunately, it was soon applied to other parts of Europe and was used as a general scheme of classification both there and in America until after 1800. Yet obviously it could not serve as a universal scheme unless all mountain ranges were of the same date and had a similar history. We now know, as Arduino did not guess, that some mountain ranges are ancient and others relatively young, and that the granite or metamorphic core of one range can not be assumed to be of the same date as that of another remote mountain system. As this fact was realized, about 100 years ago, Arduino's scheme of classification was abandoned and the terms Primary and Secondary were dropped, but, curiously, the term Tertiary was perpetuated and used for the pre-Glacial formations that we now call Cenozoic, while the term Quaternary persisted

for the deposits of the Pleistocene ice age. It is still common practice to subdivide the Cenozoic rocks into Tertiary and Quaternary systems, but this is certainly no longer justifiable; the Quaternary (= Pleistocene) is merely a short epoch of the Cenozoic era of which there is yet but a single period. The words Tertiary and Quaternary are vestiges of a misconception long since outgrown, and they should be abandoned.

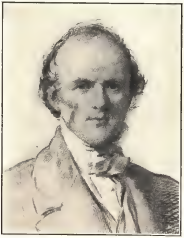


FIG. 252. Sir Charles Lyell (1797–1875).

The Cenozoic rocks were first critically studied in the Paris basin, where richly fossiliferous marine strata alternate with nonmarine formations. As the beautifully preserved faunas of these rocks were described and analyzed by the French paleontologists, notably by Deshayes, it became evident that the uppermost marine beds contained many species of shell-bearing molluscs that still live in modern seas, and that fewer and fewer of these living forms were present in successively older horizons. Grasping this idea, the great English geologist, Lyell, proposed a classification based on the percentage of still-living shelled invertebrates, and coined names for several *series* of the Cenozoic rocks accordingly. This scheme as eventually perfected is still in use, and may be expressed in tabular form as follows:

Pleistocene series (Gr. *pleistos*, most, + *kainos*, recent)	90–100%	modern	species
Pliocene series (Gr. *pleion*, more, + *kainos*)	50– 90%	"	"
Miocene series (Gr. *meion*, less, + *kainos*)	20– 40%	"	"
Oligocene series (Gr. *oligos*, little, + *kainos*)	10– 15%	"	"
Eocene series (Gr. *eos*, dawn, + *kainos*)	1– 5%	"	"
Paleocene series (Gr. *palaios*, ancient, + *kainos*)	0	"	"

Lyell originally proposed only the three terms, Eocene, Miocene, and Pliocene; the others have been added later. It is now known that the exact percentage of living species in rocks of a given date varies from region to region and is not a satisfactory basis of correlation,

Fig. 253A (left). Eocene paleogeography. Note that shallow sea overlapped most of the present Atlantic and Gulf Coastal Plain and reached northward to Cairo, Illinois.

Fig. 253B (right). Oligocene paleogeography. Note that the Cordilleran region is now nearly peneplaned.

Fig. 253C (left). Pliocene paleogeography. Renewed uplift and deep erosion have now restored strong relief in the Rocky Mountain region, and the Basin and Range Province has developed its modern aspect.

but the six series of strata (and six epochs of Cenozoic time) are nevertheless recognized throughout the world.

The Cenozoic history will be treated at greater length than that of previous periods because we can read more detail from the rocks and because they help to explain the features of our modern world.

Cenozoic History of North America

At the close of Cretaceous time North America assumed approximately its present size and configuration. The Atlantic and Gulf coastal plains were partly submerged from Paleocene to Oligocene epochs but emerged more and more completely thereafter (Fig. 253). Small embayments covered parts of California, Oregon, and Washington, and, for a very brief time at the beginning of the era, a seaway covered a small part of the northern Great Plains. The maximum submergence, however, scarcely flooded 10 per cent of the present lands, and the average for the era was only about 3 per cent.

The stratigraphic record therefore lies chiefly in nonmarine formations which, fortunately, are both widespread and richly fossiliferous. A study of land forms also adds much to our knowledge of Cenozoic history. Remnants of uplifted peneplanes, for example, tell of erosion cycles and give a measure of uplifts in both the Appalachian and Rocky Mountain regions.

The history can best be told by natural regions, taking each in its turn.

Eastern North America

Coastal Plain Overlap. From New Jersey to Mexico the outer part of the coastal plain is formed of Cenozoic formations. Like the Cretaceous beds, they are but slightly consolidated sands, clays, and marls, dipping gently seaward. Eocene and Miocene beds are most widespread along the Atlantic coast, especially in the Chesapeake Bay region, where both are marine and richly fossiliferous. Paleocene and Eocene clays and sands are most widespread along the Gulf border, commonly reaching 100 to 200 miles inland, and in the Mississippi Valley extending up to Cairo, a distance of 600 miles from the coast. In the central and western Gulf Coastal Plain the Paleocene (Midway) and early Eocene (Wilcox) formations are largely nonmarine and contain much lignite, showing the influence of the Mississippi River and its tributaries, which maintained a broad swampy coastal lowland here during early Cenozoic time.

Oligocene formations are in general less extensive, but in Florida and Central America they are widespread. In both these regions they are largely calcareous, but in the central and western Gulf area, where the influence of the Mississippi River was strong, the Oligocene is represented by thick clays and sands. Miocene and Pliocene formations are generally still more restricted, showing that the eastern and southern margins of the continent were progressively emerging.

Along the Atlantic border the Cenozoic formations form a great wedge, thickening seaward to beyond the present coast. From a feathered edge at their landward margin, they thicken to 700 to 1000 feet at the coast. A deep well on the barrier beach at Cape Hatteras, however, has revealed a thickness of 3034 feet of Cenozoic strata.[1] Not only do these formations dip seaward, but the older ones dip more steeply than the younger, proving that the continental shelf has been tilted somewhat during deposition.

Along the central Gulf border rapid subsidence has been counterbalanced by the growth of the Mississippi delta, and there Cenozoic formations reach an impressive thickness. Oil wells along the Louisiana coast are still in Miocene beds at a depth of 12,000 feet, and a study of regional dips and data from deep wells indicates a thickness of probably 30,000 feet of Cenozoic deposits under the coastal margin of Louisiana.[2] This is more than twice the maximum depth of the Gulf of Mexico and indicates excessive downwarping and suggests a geosyncline in the making (Fig. 254). The axis of this trough approximately parallels the present coast line of Louisiana and Mississippi.

Florida is made largely of Cenozoic limestones resting on a Cretaceous floor. These reach a maximum thickness of more than 5000 feet and represent all the epochs of the Cenozoic. For the most part they are clearly the deposits of a shallow sea and indicate that Florida was not a peninsula but a shallow submarine bank during most of the era. The finding of vertebrate fossils near Gainesville, however, has led to the discovery that during a part of the Miocene epoch a large low island existed over the central part of the state.[3] A fauna of 22 species, including three-toed horses, deer, rhinoceroses, and carnivores, was found in the fill of a stream channel that was cut during the period of emergence. There is also reason to believe that central Florida was emergent at the close of the Eocene epoch, and perhaps for short periods at other times in the era. Until the Miocene, Florida was too far from shore to be reached by detrital sediment, but since that epoch its eastern border has received considerable fine sand, car-

ried southward by shore currents from the streams that reach the Carolina coast. This, for example, is the source of the sand at Daytona Beach.

Origin of the Gulf of Mexico. A belt of Cretaceous and Cenozoic formations encircles the Gulf of Mexico, forming a low coastal plain from Florida to Yucatan. These formations obviously accumulated under conditions approximating those of the present, and make it certain that the Gulf of Mexico was then in existence. Deep wells

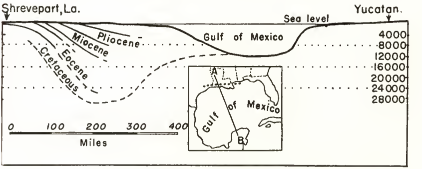


FIG. 254. Section across the Barton geosyncline and the Gulf of Mexico. The inset shows the position of the section, which runs from Shreveport, Louisiana, to Yucatan. The axis of the geosyncline follows the broken line in the inset map. Depths below sea-level indicated in feet. Modified from Barton, Ritz, and Hickey.

have revealed that Jurassic formations also underlie the western Gulf coastal plain, dipping seaward with the Cretaceous beds.

On the contrary, the pre-Jurassic rocks of the Gulf region have a very different arrangement. In the Antillean Islands they are metamorphic and volcanic and appear to be remnants of a deformed land mass. In Florida a deep well has revealed Cretaceous beds resting on deformed Cambrian or early Ordovician strata.[4] Furthermore, the late Paleozoic formations of the Ouachita trough indicate that Llanoria was a rugged upland in the western Gulf region as late as Permian time. It may be inferred, therefore, that this great depression began to form in Jurassic time and that it was well outlined in the Cretaceous period; but its present depth may be the result of Cenozoic movements.

Sculpturing of the Appalachians. At the beginning of the Cenozoic era nearly all the Appalachian region was peneplaned, the exceptions being a chain of monadnocks rising to 2000 or 3000 feet along the border between eastern Tennessee and North Carolina, and scat-

tered hills in northern New England. These unreduced areas form the crest of the modern Great Smokies, the summit of the White Mountains, and such scattered peaks as Mount Katahdin and Cadillac Mountain in Maine; they show no evidence of ever having been reduced to a level summit. Elsewhere in the Appalachian region, however, remnants of a widespread and remarkably flat erosion surface may be seen in the even crests of the highest ridges (Fig. 255) and in the summits of the Allegheny Plateau. This old surface has been

George H. Ashley.

FIG. 255. Remnants of the Schooley peneplane are seen in the accordant crests of these Appalachian folds. The view is westward into the Susquehanna Gap at Harrisburg, Pennsylvania, showing Kittatinny Mountain (*k*) with Second Mountain (*s*) and Peters Mountain (*p*) beyond it.

named the *Schooley peneplane.* When it was formed, the surface must have been near sealevel, and the region was obviously a low plain.

The present mountains are therefore due almost wholly to Cenozoic changes. However, they are not the result of either folding or faulting but of (1) *gentle regional upwarp,* which produced the present elevation, and (2) *sculpturing by erosive agents* that have carved out the weaker rocks and created the local *relief.* The mountain *structures* were already present, inherited from the Appalachian revolution and the Palisade disturbance.

The erosional history of the region is suggested in Fig. 256. After the completion of the Schooley peneplane (block 2), at a time not yet accurately dated, the region was gently arched and uplifted a few hundred feet (block 3). The streams then incised themselves to the new baselevel and opened out extensive lowlands on the weak formations, while the resistant rocks stood up as ridges (block 4). Rem-

nants of these flat lowlands are still conspicuous about Harrisburg, and this flat erosion surface, present on the weak formations only, has been named the *Harrisburg surface.*

A second gentle upwarp along the axis of the Appalachians caused the streams to incise their valleys into the Harrisburg surface and to

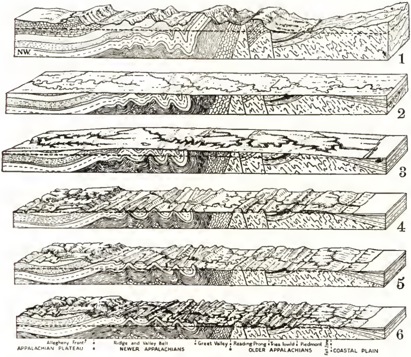


FIG. 256. Evolution of the modern topography of the Middle Appalachian region:

1. Rough topography of early Jurassic time, resulting from dissection of the structure produced by the Appalachian revolution and the Palisade disturbance.
2. Development of Schooley peneplane.
3. Arching of Schooley peneplane and incision of drainage.
4. Dissection of Schooley peneplane and local development of Harrisburg erosion surface beveling belts of weak rock.
5. Further uplift and dissection, with development of a lower erosion surface (Somerville) beveling only the weakest rocks.
6. Latest uplift and dissection. Modified slightly from D. Johnson.

excavate new lowlands of more local extent at a lower elevation (block 5). Still younger and more frequent uplifts of this sort have given rise to strath terraces along the major streams as they carved their present deep valleys. Thus by a series of gentle uplifts the Schooley peneplane has been warped up to its present maximum height of about

4000 feet along the crest of a broad simple arch, and the ridges and valleys have been etched into relief. From an axis running near the eastern edge of the Allegheny Plateau, the surface of the old Schooley peneplane slopes gently away to the east, and possibly to the west, declining but a few feet to the mile. It is preserved only on the most resistant rocks and has been completely destroyed throughout most of the piedmont belt. If it could be restored, it would have the form of a vast low arch several hundred miles wide and less than one mile high along the crest of the Appalachians. Near the present coast it would descend to sealevel and pass under one of the coastal-plain formations, for it is clear that, as the Appalachian arch came up, the continental shelf was depressed and tilted eastward. If stages of uplift in the mountains could be correlated with deposits in the coastal-plain region, the erosional history could be dated in detail, but unfortunately such correlations are not yet secure.

The Central Interior

Throughout Cenozoic time the great interior of the continent stretching westward from the Appalachian Plateau to the Great Plains was a lowland undergoing but slight degradation. The stages in its development are far more obscure than are those of the Appalachian region. River gravels widely distributed over the interstream areas bear evidence that the surface has been reduced to its present form by long-continued stream erosion and mass wasting.

In the Great Lakes region, where the Paleozoic formations overlap upon the Canadian Shield, the beveled edges of the more resistant limestones were brought into relief as cuestas, while the weaker formations were reduced to broad lowlands which, in the Pleistocene epoch, were modified by glaciers to form the basins of the Great Lakes.

Decay and Rebirth of the Rockies

Basin Filling and Peneplanation. Nearly all the major *structures* of the Rocky Mountains date from the Laramide revolution at the end of the Cretaceous. As noted before, the folding and faulting continued locally into the Eocene, and died out gradually. This left the region bold and mountainous in early Cenozoic time.

Among the ranges there were several great structural basins which have persisted, with little deformation, up to the present (Fig. 257). Such are Powder River, the Big Horn, and Green River basins of Wyoming, and the Uinta basin and North and South parks in Col-

FIG. 257. Structural basins within the middle and southern Rocky Mountains. The topography is that of the present, but the structure dates from the Laramide revolution. Drawn by Milton Wallman.

orado. As the mountains were eroded, the sediment converged into these basins, where much of it was trapped. Fans formed about the margins, but most of the debris was spread as broad alluvial deposits across the basin floors. Thus they were gradually filled as the mountains were worn down. Meanwhile, through-flowing streams were aggrading the plains region east of the Rockies. By the middle of the era the intermont basins were full and the mountains were largely peneplaned to the level of this surface of aggradation, as represented

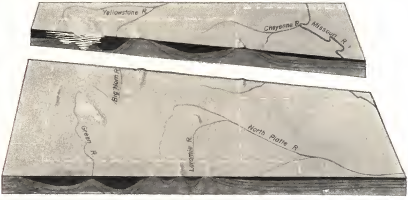


FIG. 258. Block diagram of the middle Rocky Mountains and part of the Great Plains as they were in Miocene time, when the basins were filled with Cenozoic deposits (*black*) and the ranges were peneplaned to the level of this aggraded plane. Monadnocks mark the sites of the chief ranges. The block has been cut in two, and the pieces have been parted to show the structure along a line passing through Yellowstone Park and the Black Hills. In the area of Yellowstone Park and the Absaroka Plateau, volcanics (*white*) largely replace the sedimentary deposits. The streams flow for the most part upon alluvial deposits which hide the buried ranges. Suggested by a figure by Atwood and Atwood.

in Fig. 258. Along the axes of some of the ranges, rounded monadnocks stood a few hundred or even 2000 to 3000 feet above the peneplane, but for the most part the mountains were then buried in their own debris, and the streams wandered widely over this thick alluvial cover.

This flat surface of combined erosion and deposition was probably 2000 or 3000 feet above sealevel, because the streams had hundreds of miles to flow before reaching the sea and even a very low gradient would leave considerable altitude at their source. Peneplanation had been accomplished by late Oligocene time.

Cascadian Uplift and Erosional Sculpturing. In Miocene and Pliocene time uplift was resumed, not in the form of local deformation but rather as a broad upwarp of the whole region into a low arch

hundreds of miles across. It correlates in time with the Cascadian deformation farther west, and may therefore be spoken of as a Cascadian uplift. This movement continued intermittently, but with acceleration, to a culmination in the late Pleistocene, and brought the peneplaned surface to a maximum elevation of 10,000 to 11,000 feet along the continental divide. With this uplift the streams were rejuvenated and began to deepen their valleys, to re-excavate the basins, and to sculpture the exhumed mountain masses. Thus the *height* of

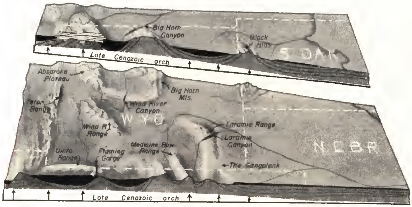


Fig. 259. Block diagram of the same region as Fig. 258, showing the present relief which is due to (1) broad regional arching during post-Miocene time, and (2) excavation of much of the weak fill from the basins. In the removal of the Cenozoic fill the streams were in many places superposed on the ranges, which they now cross in imposing canyons.

the Rockies is due to broad regional upwarp, but their present *form* and *relief* were determined by late Cenozoic erosion (Fig. 259).

Thus far it has been assumed that all parts of the Rocky Mountain region were peneplaned at the same time, and only once. This picture is undoubtedly too simple. Within a region so vast, the ranges possess individuality in structure and in lithology, and probably moved with some independence. The final uplift was long and intermittent, and a series of partial peneplanes were probably formed locally as the baselevel changed—indeed, there is clear evidence of more than one in many of the ranges. Nevertheless, in most parts of the region, remnants of one peneplane are so much more striking than any others that they appear to belong to one general *Rocky Mountain peneplane*. If, instead of one, there are several peneplanes in the Rocky Mountains, then the history is more complicated in its detail, but in fundamentals it is essentially as outlined above.

CARL O. DUNBAR.

Fig. 260. Peneplane on the granite summit of the Laramie Range. The view is north from a point near Buford, Wyoming. Monadnocks rise above the peneplane in the distance at the left.

Evidence of the history just sketched may be seen in (1) peneplane remnants still preserved along the summits of most of the ranges, (2) remnants of the Cenozoic formations around the margins of the basins, (3) superposition of many of the streams across the present ranges, and (4) the stratigraphy of the Cenozoic formations in the High Plains east of the Rockies.

These features are illustrated in Figs. 259 and 261. A particularly fine peneplane remnant may be seen along the summit of the Laramie Range in southeastern Wyoming. Here, at an elevation of 8000 feet, is a nearly flat surface 10 or 12 miles wide, cutting across granite and other types of igneous rock of the mountain core (Fig. 260). "Roads run in almost every direction; and the Union Pacific Railroad crosses the divide, not through a deep pass but across an open plateau. At the station of Sherman one may look for miles in almost any direction, and it is with difficulty that he realizes that his viewpoint is 8000 feet above sealevel, or as high as the summit of many of the rugged mountains of the Northwest" (Blackwelder).

East of the Laramie Range lie the High Plains, capped by Miocene (and locally Pliocene) beds. Their surface is extraordinarily flat and slopes gently eastward to an elevation of not over 2000 feet in central

Nebraska and Kansas. This great flat area is a remnant of the aggraded plain that existed when the mountains were peneplaned. Generally its most elevated western margin has been dissected and eroded back several miles from the mountain front, especially where large streams cross it, but locally in southeastern Wyoming it extends up to the mountains, rising to the level of the summit peneplane. Here it forms the "Gangplank" (Fig. 259) by which the Union Pacific Railroad crosses the mountains from the plains. Even where the High Plains beds have been eroded back several miles it can be seen that, if they were projected toward the mountains, their surface would meet the peneplaned summit.

Several miles north of the "Gangplank," the Laramie River crosses the range in a granite gorge more than 1000 feet deep. It rises west of the range and flows northward for some 50 miles along the floor of Laramie basin at an elevation of less than 7000 feet, and then turns east and cuts through the range instead of following the lowland northward to the Platte. Such an anomalous course is easily understood if the Laramie basin was once filled with sediment that slightly covered the range as represented in Fig. 258, for then the stream flowed on a graded plain from which it was superposed on the range after uplift. The Cenozoic fill has been almost completely removed from Laramie basin, but a telltale remnant still exists along its western margin, flat-lying along the front of the Medicine Bow Range at an elevation of 8500 feet. The greatest remnants of Cenozoic deposits at high altitudes, however, are along the southern end of the Absaroka Range, where Eocene and Oligocene strata are interbedded with, and protected by, volcanics. Here flat-lying Oligocene strata at an elevation exceeding 10,500 feet rim the northern side of the Wind River basin.

The course of Laramie River in crossing the range is not exceptional; the major streams flow radially out of the Rocky Mountains, crossing basins and ranges alike (Fig. 261). As shown in Fig. 259, Big Horn River, originating in the Wind River basin, cuts through the Owl Creek Mountains and flows for 100 miles across Big Horn basin, only to turn east and cut through the north end of the Big Horn Range in an imposing chasm. Likewise, Green River flows south across Green River basin, swings east along the north side of the Uinta Mountains, and then cuts through them in the magnificent Flaming Gorge. Farther south, South Platte River, heading in South Park at an elevation of about 9000 feet, flows northeast through the

Front Range in another great gorge; and the Arkansas, after flowing across South Park basin, cuts through the Front Range in picturesque Royal Gorge, whose sheer walls tower 1400 feet above the stream.

All these and other anomalous features of the drainage find a simple explanation in the fact that the basins were formerly filled completely with Cenozoic sediments until the ranges were covered where the streams now cross them.

U. G. Cornell.

FIG. 261. Canyon of North Platte River near the mouth of the Sweetwater, southwest of Alcova, Wyoming, cut to a depth of 450 feet in granite.

Stratigraphy of the Cenozoic Deposits. The fluvial deposits that were spread as an immense debris apron east of the Rockies during Cenozoic time have been partly destroyed by later erosion along both their eastern and western margins, but the great central portion is still intact in the High Plains. Here they include clay, silt, and sand, with linear bodies of coarse sand and gravel marking old stream channels. In general the beds are weak, and in areas of rapid erosion appear as "badlands" (Figs. 263, 264). Much volcanic ash, derived from sources farther west, is included in the stream-laid deposits.

The thickness of the entire deposit ranges up to 2000 feet over extensive areas but is nowhere much greater. It includes formations of Paleocene, Oligocene, Miocene, and Pliocene dates, but none of these was continuous over the whole region. They were deposited by streams flowing nearly at grade and ever seeking the lowest places to drop their loads. The result is an intricate patchwork of formations, mostly local in character. A few are more widespread and represent times of more general deposition.

The oldest beds here present constitute the *Fort Union formation* of Paleocene date, which occupies a vast area in the northern Great Plains, chiefly in the Dakotas, Wyoming, Montana, and Alberta. It includes friable yellow sandstones, somber gray shales, and many

zones of coal. Over a considerable area in the center of the Dakotas there is present at its base the *Cannonball marine member*, with oyster banks and other evidence of shallow brackish and marine water (Fig. 262). A fauna of about 150 species of marine animals has been identified from these beds (about 80 molluscs and 64 foraminifers). Until recently this marine zone was referred to the underlying Lance (= Laramie) formation of latest Cretaceous date, but study of the associated land plants and of the Foraminifera indicates that the Can-

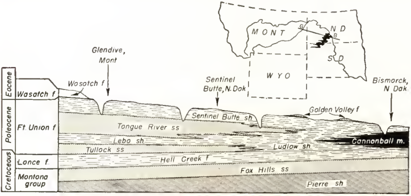


FIG. 262. Stratigraphic section showing the relations of the Cannonball marine member of the Fort Union formation. The inset map shows the outcrop of the Cannonball member (*black*) and the line of the section, *G–B*. The Golden Valley formation of Eocene age appears as outliers near Bismarck, North Dakota. Length of section, about 200 miles; vertical scale greatly exaggerated.

nonball horizon is Paleocene; [5] and if so, it must be transferred from the Lance to the Fort Union formation. Thirty-eight species of the Foraminifera occur also in the Paleocene (Midway group) of the Gulf coast, and of these 13 are limited elsewhere to that group.

In the plains, the Fort Union formation is the chief coal-bearing horizon. Here it has yielded abundant plants, but almost no vertebrate remains. Farther west, however, it holds an amazing array of strange, small, primitive mammals.

With the exception of small areas of Early Eocene (Wasatch) beds in eastern Montana and the Dakotas,[6] no true Eocene formations occur east of the Rockies, although they are thick and widespread in the intermont basins (Fig. 266). Evidently by this time relief in the mountains was reduced somewhat, and the streams were at grade. In the plains the Paleocene beds are succeeded by the Oligocene *White River group* which is widespread in Montana and Wyoming, reaching

eastward into the Dakotas and southward into Nebraska. It forms the Big Badlands southeast of the Black Hills (Figs. 263, 264) and is one of the most prolific sources of fossil vertebrates in the whole Rocky Mountain region. It ranges from 200 to 500 feet in thickness and consists generally of clay and fine silt along with much volcanic ash. The general lack of sands and gravel indicates that the region farther west had but slight relief at this time.

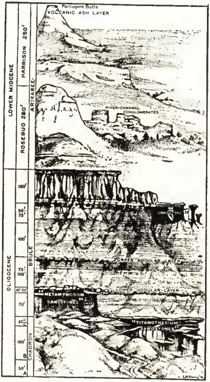


Fig. 263. Idealized panoramic section of the Big Badlands of South Dakota. After H. F. Osborn, U. S. Geological Survey.

The overlying *Arikaree group*, of Miocene date, is relatively coarser, including great quantities of sand. It extends farther than the Oligocene beds and locally reaches a thickness of about 2500 feet, though in most places it is far thinner. Recently the *Hemingford group* was defined to include Upper Miocene formations, which in the past have been included in part in the Arikaree. Evidently uplift was under way in the mountain region, and the streams emerging onto the plains were once again heavily laden with sand as well as mud.

The Pliocene is represented by the *Ogallala group*, which ranges from 300 to 500 feet in thickness and, like the Miocene beds, consists of clay, fine silt, sand, and gravel, mostly unconsolidated.

Pleistocene deposits include glacial drift and loess north and east of the Missouri River, and very limited and patchy areas of bedded sand and gravel farther south.

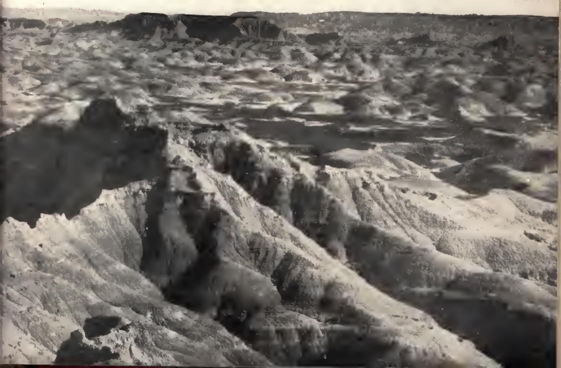
The character of these formations in the High Plains obviously reflects the erosional history of the mountains (Fig. 265). The coarse, sandy Paleocene deposits indicate high relief in the mountain area as the streams emerged heavily loaded with sand and gravel as well as mud. The lack of Eocene deposits shows that the streams then flowed at grade; evidently the relief in the mountains was con-

siderably reduced by this time. The very fine grain of the widespread Oligocene deposits, both here and in the intermont basins, indicates very low relief, and the upper surface of these beds is to be correlated with peneplane remnants on the summits of the Front Range. The coarser nature and the considerable thickness of the Miocene beds show that uplift in the mountain region had been resumed and the streams were once again emerging heavily laden with sand. By Pliocene time arching along the axis of the Rockies had tilted the surface of the High Plains eastward so that the streams were again at grade, in most places carrying their load of debris through to the Mississippi River.

The intermont basins are occupied chiefly by Paleocene and Eocene deposits which reach an aggregate thickness of several thousand feet. Like the Cenozoic formations of the plains, they are mostly fluvial deposits of clay, silt, and sand. Thick basal and marginal conglomerates occur in places where alluvial fans were built at the mouths of torrential streams. Deposition was independent in the several basins,

N. H. DARTON, U. S. GEOLOGICAL SURVEY.

Fig. 264. The Big Badlands of South Dakota. Oligocene (Brule clay) in the foreground.



the accumulation depending on the amount of subsidence; and, since the warping was irregular and intermittent, there is no complete record in any single basin. Nevertheless, the abundant fossil mammals permit a correlation of zones from basin to basin and the building up of a composite sedimentary section of these oldest Cenozoic formations amounting to between 10,000 and 20,000 feet. (For basins, see Fig. 257.)

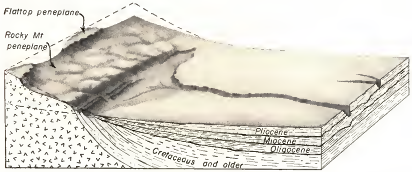


FIG. 265. Idealized diagram to show the relation of sedimentary deposits in the High Plains to erosion surfaces in the Rocky Mountains. It is drawn on the assumption that the Flattop peneplane was completed during late Oligocene time and the Rocky Mountain peneplane late in the Miocene epoch before renewed uplift started canyon-cutting in the mountains. If this be true, the upwarped Flattop surface was once continuous with the upper surface of the Oligocene beds, and the Rocky Mountain erosion surface originally joined the erosion surface separating the Miocene from the Pliocene formations. Although these correlations appear probable, they are not certainly proved because after the latest upwarp the streams have not only cut valleys in the deposits of the High Plains but also have stripped back their western margins most of the way along the front of the mountains, leaving a gap several miles wide between the remnants of the erosion surfaces in the mountains and their counterparts in the High Plains. Adapted from an unpublished figure by R. F. Flint.

These deposits, like those of the plains, commonly form badlands, a typical view of which is shown in Fig. 264. Four major groups are widely recognized, three of them named from the basin where best exposed. The oldest of these is the *Paleocene horizon,* which embraces the *Fort Union* and equivalent beds. Next comes the *Wasatch formation* (Fig. 266), marked by the first great invasion of modernized mammals, including the "dawn horse," *Eohippus.* Above this comes the *Bridger formation,* with younger mammalian faunas, and finally the *Uinta formation,* with the last and largest of the archaic mammals represented by the grotesque uintatheres.

The *Green River basin* of Colorado and Wyoming was occupied by a vast shallow lake during much of middle Eocene time, and here accumulated the fine, evenly bedded oil shales (so called because they

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Fig. 266. Lower Eocene (upper Wasatch) exposures along Cottonwood Draw near Lost Cabin, Wyoming.

yield oil by destructive distillation), of an average thickness of 2000 feet. Around the margins of the basin, however, the lake beds grade laterally into fluvial sediments of the Wasatch and Bridger formations. Most of the Green River strata are laminated, and, on the assumption that the layers are seasonal, it has been estimated that their deposition required 6,500,000 years. On this basis the Wasatch required 11,000,000 years, the Bridger 4,000,000, and the Uinta nearly 2,000,000.

In Montana, there are rather extensive lake deposits of Oligocene date formed in broad valleys that were obstructed by warping and local faulting. These are the Bozeman Lake beds. Near Florissant, Colorado, there was a similar but smaller intermont lake in early Miocene time, and its deposits form one of the richest of all localities for fossil insects and plants. The sediments are largely of volcanic ash, which appears to have overwhelmed and buried the life in its fall. The John Day basin of central Oregon was another intermont basin encircled by active volcanoes during late Oligocene time, and here was formed one of the richest known deposits of Cenozoic fossil mammals.

Central Cordilleran Region

Figure 267 displays the relations of the major structural units of the Cordilleran region. On the east lie the Rockies and on the west

Fig. 267. Relief model of the Cordilleran region, showing the relations of its major structural elements.

the Sierra Nevada and the Coast Ranges, while the central Cordilleran region is formed by the Colorado Plateau and the Basin and Range Province (which farther north gives way to the Columbia Plateau). The Basin and Range Province, with an average height of 6000

feet, lies more than a mile below the crest of the Sierra Nevada, and a few thousands of feet below the Colorado Plateau. Its ranges are tilted fault blocks of Mesozoic and Paleozoic rocks flanked round and partly buried by the Late Cenozoic sediments. The Colorado Plateau, on the contrary, consists of relatively flat-lying Mesozoic and Paleozoic formations at an elevation ranging from 7000 to 11,000 feet. The rocks of the plateau were thrown into broad swells, with local monoclinal flexures, during the Laramide disturbance, and have been broken by a number of normal faults during Cenozoic time; yet, by and large, it is a unit contrasting in simple structure with the Basin and Range Province on the one side and the Rockies on the other.

Origin of the Basin and Range Province. The Basin and Range Province (Fig. 267) lies in the zone of the enormous Laramide thrusts. It is probable that those movements continued into the Eocene, and that during Early Cenozoic time the region had a high mountainous surface and exterior drainage. For this reason Eocene and Oligocene strata are practically absent.

Miocene formations are present, however, and are locally of great thickness. Their character speaks eloquently of the events that were occurring. For example, in southern Nevada the Miocene deposits begin with coarse conglomerate that ranges up to 3000 feet in thickness and lies across the beveled edges of Early Mesozoic and Paleozoic strata. The conglomerate varies greatly in thickness within short distances and includes angular and subangular fragments of all the older rocks. Overlying the conglomerate are clays and silts, including thick beds of gypsum, magnesite, and borax. The conglomerate is clearly the coarse debris of fans formed in a region of bold relief, and the clays and silts, with their saline deposits, could have formed only in arid basins of interior drainage much like the present basins. In short, normal faulting had begun on a grand scale, and the Basin and Range Province had its inception in the Miocene. As the new ranges were greatly elevated during the Pliocene epoch, the intervening basins, all in the rain shadow of the Sierra Nevada, assumed a desert character like that of today. The faulting was only begun in late Miocene time, for the deposits of that age were themselves later steeply tilted and truncated so that they now lie with strong angular unconformity below the Pliocene beds. The latter, ranging up to 1800 feet thick and including gypsum and salt beds as much as 100 feet thick locally, bear witness to continued deepening of the basins. The well-defined fault scarps, as well as historically dated faulting, prove that the

movements are still going on. In résumé, this province came into existence through profound normal faulting that began in Miocene time, reached its climax during the Pliocene, and has continued to the present.

Stripping and Canyon Cutting in the Colorado Plateau. The Colorado Plateau is remarkable for tabular plateaus, cliff-bound mesas, and deep canyons, all of the most impressive magnitude. Gently dipping formations of Triassic, Jurassic, and Cretaceous age rise one

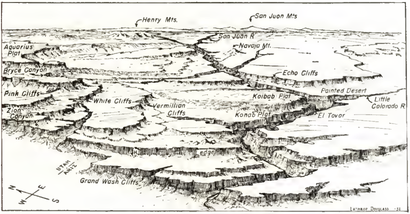

FIG. 268. Aerial view of the Grand Canyon district, looking east-northeast across the mouth of the canyon where it cuts through Grand Wash Cliffs and enters the lower country to the west of the Colorado Plateau. The Grand Canyon proper extends up to the mouth of the Little Colorado River, above which the gorge is called Marble Canyon as far as Echo Cliffs, and above that, Glen Canyon.

above another in terraced plateaus bounded by unscalable cliffs many hundreds of feet in height (Fig. 268). These cliffs are the receding edges of resistant formations, truncated during an Early Cenozoic erosion cycle; and their grandeur bears witness to the vast amount of stripping that the region has suffered since the end of the Cretaceous.

The region was more or less extensively covered by Eocene sediments (Fig. 269) like those of the Green River and San Juan basins, and since no Oligocene formations are present, it appears that by Oligocene time the area had a low relief and well-established exterior drainage.

At some later date there was regional uplift with more or less profound normal faulting. This started a new cycle of erosion that resulted in extensive degradation but left no later Cenozoic sediments within the region. It is therefore difficult to date precisely the stages

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Fig. 269. Eocene (Wasatch) strata in the north rim of Bryce Canyon, Bryce Canyon National Park, Utah. View along the rim from Sunrise Point, Boat Mountain in the middle background. These Eocene beds form the Pink Cliffs of the Colorado Plateau (Fig. 268).

of uplift or to determine how many cycles of erosion are represented.

The presence of Eocene beds unconformably overlying truncated folds in the Mesozoic formations (Fig. 270) indicates that a large amount of the degradation and stripping had been accomplished during the interval between the Laramide uplift and the local beginning of Eocene deposition. On the other hand, the Eocene beds mantled an old surface of low relief; hence the present ruggedness of the region has come into being during later Cenozoic time.

The Grand Canyon proper is incised in a part of the area that was most uplifted, though it has since been reduced by erosion to a level 2000 or 3000 feet below the plateaus farther north. The Grand Canyon district is, in fact, a broad, nearly flat-topped dome about 100 miles across, from which more than 6000 feet of Mesozoic strata has

been stripped (Fig. 271). Over this dome the strata dip gently, but they are more abruptly bent down at its eastern margin in a pair of great monoclinal flexures. The west side of the dome has broken down along a great normal fault, leaving the Grand Wash Cliffs facing westward toward the lower country of the Basin and Range Province.

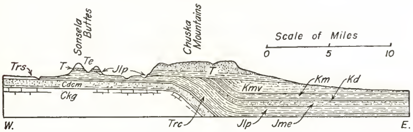


FIG. 270. Section through the Chuska Mountains, northeastern Arizona, showing early Cenozoic (Eocene?) sediments (*T*) resting unconformably on truncated Cretaceous (*Kd*, *Km*, *Kmv*) and older formations in the Defiance monocline. After H. E. Gregory, U. S. Geological Survey.

Before the cutting of the canyon began, the stripping of this huge dome had reached almost its present stage and left the high cliffs of the region about as they are now. Although these towered above the intervening benches with a relief of a few thousands of feet, the region as a whole was much nearer sealevel than at present. The final uplift of the region led to a reorganization of the drainage, initiated the present Colorado River system, and started the canyon cycle.

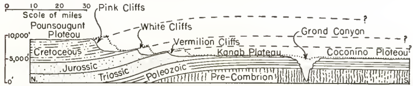


FIG. 271. North-south section across the Grand Canyon region south of Kanab, Utah, showing relation of the present surface to the structure. The base line is drawn at sealevel. Dashed lines indicate the position Mesozoic formations would assume if the eroded portions were restored; dotted line indicates the profile before the last uplift, which initiated the cutting of the Grand Canyon.

The date of this uplift can be determined west of the Grand Wash Cliffs where the river emerges from its canyon and crosses the Great Basin, flowing over Miocene beds that are known from their salt and gypsum deposits to have formed in arid basins without exterior drainage. Obviously, the Colorado River did not exist, or at least did not

have its present course, in Miocene time. Hence the great uplift of the plateau and the carving of the canyon are the work of Pliocene, Pleistocene, and Recent time.[7]

Building of the Columbia Plateau. North of the Basin and Range Province, and occupying the area between the Northern Rockies and the Cascade Ranges (Fig. 267) lies the Columbia Plateau, a vast upland built of Cenozoic basalt flows that cover an area of more than 200,000 square miles and reach a maximum thickness of over 5000 feet. The total volume of the lava is estimated at 24,000 cubic miles. For the most part it emerged through fissures in a very fluid condition and spread widely in sheets a few feet to a few tens of feet thick. These flows sought the lowest places, filling the old valleys and encroaching on the flanks of hills and mountains. In time the pre-basalt topography was buried, and a relatively flat basalt plain was constructed.

The larger streams, such as Snake and Spokane rivers, have since cut through the lava flows in some places, especially near the eastern margin of the plateau, revealing a pre-basalt surface of considerable relief (at least 2500 feet), formed on schists, granites, and other pre-Cenozoic rocks.

As the flows spread over this region, they interrupted the drainage, damming streams and giving rise to local lakes and swamps in which sediments accumulated, entombing plant and vertebrate remains. Such fossiliferous deposits now locally interbedded with the lavas serve to date the eruptions. A noteworthy example is the *Latah* formation exposed in the valley of Spokane River near Spokane, Washington. Consisting of sands and clays and including much reworked volcanic ash, it has an exposed thickness of about 500 feet, but deep wells reveal 1500 feet of such beds with interbedded lava flows. The deposit lies at the eastern margin of the Columbia Plateau and was formed in swamps and lakes created when the lava, flowing eastward, dammed the streams that flowed westward from the Rocky Mountain region in Idaho. The Latah formation has yielded a large number of well-preserved Miocene plants.

A similar deposit is the *Payette* formation exposed in the Snake River Valley on the Idaho-Oregon boundary about 250 miles south of Spokane. It has yielded both plant and vertebrate fossils of Miocene date. These and similar fossiliferous deposits interbedded with the flows indicate that the major part of the basalt eruption took place during Miocene time, though in some areas it continued into the Pliocene. In fact, Snake River Valley (which forms a southeastern

lobe of the Columbia Plateau) is covered by black lavas of Pliocene and Pleistocene date in which the fresh appearance of spatter cones, like those of Craters of the Moon National Park, suggests activity within Recent time.

During eruption, and also in later epochs, the Columbia Plateau was broken locally by normal faults, and was subjected to extensive, though gentle, warping; hence the plateau surface now varies from

FIG. 272. Idealized block diagram of a part of the Coast Ranges, the California trough, the Sierra Nevada, and the Basin and Range province. The view is northward. Length of section along front face, about 250 miles. Vertical scale exaggerated about 50 times. *Gm*, Mesozoic granite; *J*, Jurassic; *K*, Cretaceous; *M*, Miocene; *P*, Pliocene; *Ple*, Pleistocene; *Pl*, Lower Paleozoic; *Pu*, Upper Paleozoic.

3000 feet to more than 8000 feet in elevation. In part, the warping may have compensated for the extrusion of the great volume of molten rock from beneath the crust.

The Pacific Border

The Cenozoic history of the region west of the Basin and Range Province is extremely complex, and not yet fully understood. As shown in Figs. 267 and 272, it embraces two great mountain chains, separated by a series of large troughs. The eastern chain consists of two independent units, the Sierra Nevada of California and the Cascade Mountains of Oregon and Washington; the western chain embraces the Coast Ranges. The latter continue far to the north along the coast of British Columbia and have a counterpart to the

south in the peninsula of Lower California. Between the Sierra Nevada and the Coast Ranges lies the California trough, a structural basin which has its counterparts farther north in the Puget Sound basin and to the south in the Gulf of California. The history of these units is complexly interrelated.

During Cenozoic time these structural troughs were depressed as the bordering mountains rose, and the sedimentary formations of this region are enormously thick, aggregating more than 50,000 feet. The sea repeatedly invaded the California trough but seldom covered more than a small part of it, while nonmarine sediments were accumulating in other parts. The Coast Range belt was in part submerged while undergoing complex deformation (both folding and faulting), with the result that relatively small embayments subsided to receive great depths of sediment from adjacent island masses that were rising.

Uplift of the Sierra Nevada. Figure 272 shows the structure and mutual relations of the Sierra Nevada, the California trough, and the Coast Ranges of California. Although genetically related to the others, each has its distinctive form and structure.

The Sierra Nevada represent part of a colossal fault block more than 100 miles wide and 300 or 400 miles long. The eastern margin of this block has been uplifted to an elevation of about 13,000 feet (Fig. 273), and its western edge depressed perhaps 25,000 feet below

F. E. MATTHES, U. S. GEOLOGICAL SURVEY.

Fig. 273. East face of the Sierra Nevada, a great fault scarp 2 miles high. Telephoto view westward from Owens Valley, California. Compare Fig. 272.

sealevel. The uplifted part forms the Sierra Nevada, and the depressed half the California trough.

The Sierra Nevada are sculptured from this single fault block of Jurassic and older rocks, the chief mass being a granite batholith. All the structures within the range far antedate the Cenozoic. Its early Cenozoic history is obscure, but by Miocene time the region had been peneplaned. Then began an uplift accompanied by faulting along its eastern border, which transformed it into a mountain range of moderate height. Relative quiet ensued throughout Pliocene time, and the

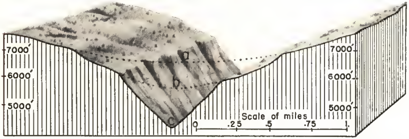


FIG. 274. Cross-profile of Merced River Valley below Yosemite Valley, showing evidence of two stages of uplift. *a*, profile of the old, broad valley, probably of late Miocene date when the region was still low; *b*, profile of the mountain valley stage (probably late Pliocene), cut after the first strong uplift and westward tilting of the Sierra block; *c*, canyon stage, cut during the Pleistocene in consequence of the last great uplift of the Sierra. After F. E. Matthes, U. S. Geological Survey.

westward-flowing streams then opened out broad valleys. About the beginning of the Pleistocene, new uplift and westward tilting began, but the great uplift occurred near the middle of this epoch, after the second glacial age. This elevation of several thousands of feet brought the mountains to their present altitude and started the westward-flowing streams cutting canyons within their broad valleys.

Evidence of these distinct stages of uplift is found in (1) the cross-profiles of the valleys (Fig. 274), and (2) the character of the deposits formed by these streams in the California trough.

Résumé of Cenozoic Orogeny and Volcanism: The Cascadian Revolution

From the foregoing account, it must be clear that the Cenozoic was an age of great crustal disturbance and extraordinary volcanic activity in the western half of North America. The Laramide thrusting died out irregularly during the long Eocene epoch, and the Oligocene was a

CARL O. DUNBAR.

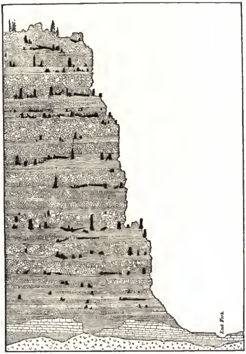
Fig. 275. Lava flows of the Absaroka Range present the appearance of horizontal strata from a distance. Looking north across Shoshone Canyon about 25 miles west of Cody, Wyoming.

time of comparative quiet during which most of the Cordilleran region was again reduced to lowlands.

A new revolution began in the Miocene and continued intermittently to its culmination in the far-flung regional uplift of the Pleistocene. This last great orogeny has been called the *Cascadian revolution.* The Cascade Mountains were in the midst of the vast area of disturbance but actually comprised only a small part of it. The movements were complex and diversified, but on the whole they were predominantly vertical movements (epeirogenic, not orogenic) accompanied by normal faulting. In this we see a marked contrast with the Laramide revolution, which involved great horizontal forces and eventually produced enormous thrust faults and great folds. During the Cascadian movements, folding was largely confined to the Coast Ranges and the Puget Sound basin. In the former it probably resulted largely from the squeezing or wedging produced by differential subsidence of fault blocks. In the Puget Sound area, where the thick Eocene beds are steeply upturned, the horizontal compression may have come from

the intrusion of a large granitic batholith into the northern part of the Cascade Mountains during Miocene time.

Throughout the Cordilleran region the last movements were chiefly those of regional uplift in late Pliocene and Pleistocene time. The greatest crustal movement in California evidently took place in middle



U. S. Geological Survey.

Fig. 276. Profile section of Amethyst Cliff in Yellowstone Park, showing remains of eighteen successive forests, each killed and buried in turn by volcanic materials. Section about 2000 feet thick.

Pleistocene time, because the later deposits lie unconformably on the deformed early Pleistocene strata.

In every respect the Pleistocene epoch is allied with the Pliocene, and if it were not for its extensive glaciation, the Pleistocene would probably never have been differentiated. The Pleistocene is clearly a part of the Cenozoic era. Whether the climax of orogeny and uplift is now past, only the future can tell; we are too close to it to judge.

J. P. IDDINGS, U. S. GEOLOGICAL SURVEY.

Fig. 277. Fossil tree trunks exposed in the face of Amethyst Cliff, Yellowstone Park. Compare with Figs. 276 and 16.

Volcanic activity occurred in the Cordilleran region during this era on a scale not approached at any other time since the remote Pre-Cambrian. Volcanoes were active at the beginning of the era in most if not all of the western states. Great basalt flows during the Eocene covered an area in western Washington and Oregon more extensive than all New England. At the same time andesitic flows built up the Absaroka Range (Fig. 275) and the plateau upon which Yellowstone Park is located, covering fault-block ranges of Mesozoic and older rocks to a depth of many hundreds of feet. Here the lavas overwhelmed forests at successive intervals of hundreds of years, as seen in Amethyst Cliff, where the stumps of eighteen successive forests stand petrified (Figs. 276, 277).

Sedimentary beds interstratified with the lava and pyroclastics along the southern border of the Absaroka Plateau prove that volcanoes were

active there during middle and late Eocene as well as Oligocene time. The older volcanics of the Yellowstone Park are also of Eocene age, and the younger ones chiefly Miocene, though present geysers and hot springs indicate that volcanic heat still smoulders.

Many explosive volcanoes were active in Oligocene time, for the White River sediments are in considerable part reworked volcanic ash. During this epoch, John Day basin in central Oregon was filled to a depth of 2000 to 3000 feet with reworked volcanic ash that has preserved an amazing array of fossil mammals.

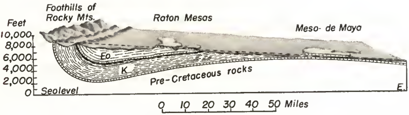


FIG. 278. East-west section through Raton Mesas and Mesa de Maya, near Trinidad, Colorado. The mesas are remnants of a Pleistocene lava flow that spread from the foothills of the Rockies almost to the Kansas line. The lava rests on beveled Eocene strata, which in turn rest on Cretaceous. *Eo*, Eocene; *K*, Cretaceous. After Willis T. Lee, U. S. Geological Survey.

The Miocene was, however, the time of truly colossal volcanism. At this time occurred most of the basic eruptions of the Columbia Plateau, Snake River Valley, and the Cascade Mountains, a vast field of basalt covering an area of more than 200,000 square miles. At the same time a great field of volcanoes in southwestern Colorado built up the San Juan Mountain mass. Volcanoes were scattered over the Basin and Range region and the Colorado Plateau, and there was extensive igneous activity in Mexico. Igneous activity in the Black Hills of South Dakota gave rise to a remarkable series of laccoliths whose partly denuded forms are now striking features of the region.

In many of these regions volcanism continued with decreased vigor through the Pliocene and into the Pleistocene, no fewer than 120 fields of volcanoes being known with cones that were still active in the Pleistocene. Near Trinidad in the foothills of eastern Colorado there are impressive features of Cenozoic igneous activity. Spanish Peaks are a pair of denuded majestic Eocene intrusives with a unique display of great radial dikes. A short distance southeast of these lie Raton

Mesas and Mesa de Maya (Fig. 278), which are remnants of Pleistocene basalt flows that spread eastward over the plains almost to the Kansas line.

Cenozoic Orogeny and Volcanism in Other Continents

The history of the Andean chain of South America paralleled that of the Rockies in many respects. Folded at the close of the Mesozoic, the Andes were extensively peneplaned during the earlier half of the Cenozoic and then, chiefly during Pliocene and Pleistocene time, were vertically elevated by several thousands of feet to their present height.

The Alpine-Himalayan systems, stretching from western Europe to the East Indies, had a complex and spectacular Cenozoic history (Fig. 279). The beginning of the Alps goes back to the Mesozoic, when a very broad geosyncline occupied by the greater ancestral Mediterranean (Tethys) spread over all southern Europe and eastward across the Himalayan region. In Jurassic time horizontal compression from the south caused two or three great folds to rise out of this sea. Although this marks the beginning of the Alpine structures, the region as a whole remained submerged during much of Cretaceous time. At the close of the Cretaceous there was further compression and some uplift, and in the Eocene the first decided thrust, but marine waters returned between the rising geanticlinal folds and persisted widely until middle Oligocene time. Then occurred the first great paroxysm of Alpine orogeny as the compression from the south caused great recumbent folds to rise as mountain arcs out of the sea, and to ride forward over the old foreland north of the geosyncline, where they piled up as a series of nappes (Fig. 279, 3).

Before these great thrusts lay a lowland, now the Swiss Plateau. Over this was spread, during late Oligocene and Miocene, a vast piedmont deposit (the *Molasse*) of sand and coarse gravel derived from the rising mountains. Most of it is of freshwater deposition like the Cenozoic deposits east of the Rockies, but marine horizons show that the sea still had access to the northern border of the Alps as late as Miocene time. In the Pliocene came further great thrusts from the south that caused the older nappes to ride out over the Molasse and buckled up the Jura folds that now form the northern front of the Alps. This also gave a great regional uplift to the entire mass, an uplift that reached its culmination in the Pleistocene.

The history thus sketched for the Alps is, in general, that of the Carpathians, the Dinaric Alps of Dalmatia, and the Himalayas. In the

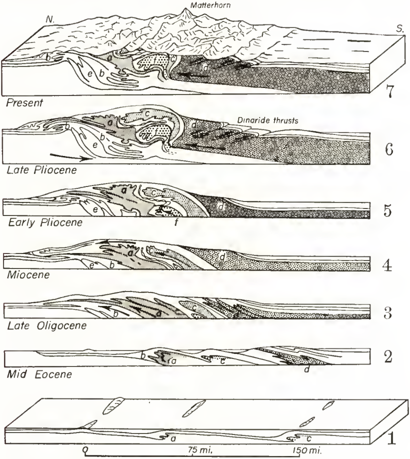


Fig. 279. Development of the western Alps. Adapted from a figure by Collet, after Argand. Block 1 represents a belt across the Alpine region in late Mesozoic time when it was still largely covered by the Tethyan sea; block 7 shows a corresponding area in the modern Alps; and sections 2 to 6 show how the modern structure developed during Cenozoic time as a series of nappes were thrust one over another toward the north. Finally, in late Pliocene time, underthrusting steepened the roots of the southern nappes and caused a series of thrusts toward the south, now seen in the Dinaric Alps. *a*, Great St. Bernard nappe; *b*, nappes of the Pre-Alps; *c*, Dent Blanche nappe; *d*, nappe of the southern Alps; *e*, Mont Blanc massive; *f*, Monta Rosa nappe.

southern one of the three ranges that make up the Himalayan system, marine Eocene formations now occur at an elevation of 20,000 feet, bearing witness to the tremendous uplift experienced by that region

since Early Cenozoic time. The foothills of the southern Himalayas are believed to have suffered an uplift of 6000 feet since the beginning of the middle Pleistocene.

Many countries also had volcanic activity during Cenozoic time. In Central America especially, and in Mexico, the Antillean islands, and the Andean Plateau, there were great outpourings of lava. The North Atlantic was also the scene of large basalt flows, now displayed in northern Ireland (Giant's Causeway), northwest Scotland, the Orkney Islands, the plateau of Iceland, and eastern Greenland. The great rift valleys of East Africa constituted another arena of great eruptions. Finally, during Pliocene and Pleistocene time, volcanic chains became active in the Mediterranean region and in Alaska, Japan, and the East Indies, completing the "Ring of Fire" around the Pacific.

Cenozoic Climates

Fossil plants throw much light on the climate of Cenozoic time. The forest trees have come down to us with only trivial change since early Cenozoic time and probably have not changed appreciably their preferred habitat. Moreover, it is well known that most of them are restricted in their distribution by rainfall and temperature, each preferring a definite environment. Accordingly, the vegetation of a subtropical lowland like Florida has little in common with that of a desert basin, or with the forests of a temperate mountain slope, or with the subarctic barrens. Thus it is possible to infer the climatic conditions under which a Cenozoic flora lived.

A comprehensive study of such material throughout western North America [8] has shown a striking change of climate since early Cenozoic time. During the Eocene and Oligocene epochs subtropical types of trees, now restricted to moist lowlands, ranged widely over the United States and Europe. Palms and alligators were then common as far north as the Dakotas, suggesting a climate like that of modern Florida and Louisiana. At the same time a moist temperate forest existed in high northern latitudes, notably in Alaska, Greenland, Spitzbergen, and northern Siberia. It was dominated by the giant redwood and included such deciduous trees as the basswood, beech, chestnut, and elm. Even cycads, magnolias, and figs then lived in Alaska. The climate was not only milder and more humid, but also more uniform than now over the far western United States, evidently because the region was generally low and the mountains were

not lofty enough to interfere seriously with the moisture-bearing westerly winds.

After Eocene time there was a slow but general southward migration of the various plant assemblages, indicating a gradual cooling of the climate that became more marked in Pliocene time and culminated in the Pleistocene glaciation. Meanwhile, in Miocene and Pliocene time, the climate became more diversified in the western United States as the rising mountains intercepted the winds, producing moist western slopes and arid regions in their lee. This diversity was not nearly so extreme or so widespread in Miocene time as it is today, though the salt and other precipitates entombed in the Miocene deposits of southern Nevada indicate rather intense local aridity in the basins then forming. Even as late as early Pliocene time, however, a flora like that of southern California was still living in western Nevada (the Esmeralda flora), indicating a rainfall of 12 to 15 inches a year in a region where the present rainfall is only 4 inches. The final uplift of the Cordilleran ranges in the late Pliocene and Pleistocene gave the intermont basins and the Great Plains their present degree of aridity.

Mention should also be made of local evidence of cold climate at the very beginning of the era. About the flanks of the San Juan Mountains in southwestern Colorado there is a deposit of tillite up to 100 feet thick (Ridgway tillite) lying unconformably on the Cretaceous and overlain by tuffs of Eocene date. These glacial deposits are so distributed as to indicate a source in the crest of the mountains some 40 miles away. The presence of such extensive valley glaciers in a region where now there are none clearly indicates that the snowfall was then vastly greater than now, or the average temperature was considerably lower, or else both conspired to produce glaciers. Unfortunately, the tillite can not be more closely dated, but it probably was formed at the time of maximum uplift at the end of the Mesozoic era, or shortly thereafter. The widespread plant evidence indicated above shows that by Eocene time warm temperate climate had spread as far north as the Arctic Circle.

Economic Resources

Petroleum. Two of the major American oil fields draw their production from Cenozoic rocks. The Gulf Coast pools of Louisiana and southeast Texas are in small domes associated generally with stock-

like plugs of rock salt that have pressed up from below into Miocene sands and clays. The California oil fields likewise draw nearly all their oil from Miocene (over 30 per cent) and lower Pliocene (65 per cent) strata.

Although the greatest American oil fields are in Paleozoic or Mesozoic rocks, it is a very striking fact that nearly all the foreign fields are in Cenozoic formations. For example, the rich Baku fields of Russia produce from the Miocene, the Galician fields from the Eocene, Oligocene, and Miocene, the Rumanian fields from Oligocene to Pliocene, those of Burma, Sumatra, Java, and Japan from the Miocene, and those of the Persian Gulf chiefly from the Miocene.

Coal. Lignite occurs in the Eocene of the Gulf Coast but is not commercially exploited. In the Puget Sound region, however, the strong folding of the coal-bearing series has advanced the Eocene coals to a sub-bituminous rank. These coals are now being extensively used west of the Sierra Nevada and Cascade ranges. Their total production up to 1939 amounted to a little over 125,000,000 tons. In several of the coal fields of Montana and Wyoming the Fort Union formation is the chief producing horizon, and the reserves in these beds are extensive. In most parts of the world, Cenozoic coals are of lignite or low-grade sub-bituminous rank and therefore of little present value.

Placer Gold. As noted before, the placers, which yield about two-thirds of the annual gold of California, were formed during Cenozoic time by streams degrading the Mother Lode belt in the Sierra Nevada. Between the Gold Rush of 1849 and the year 1946, California had produced over $2,250,000,000 worth of gold.

Metalliferous Veins. The fabulous wealth of gold, silver, and copper so widely distributed throughout the Rocky Mountain region is for the most part a by-product of the intrusions of Cenozoic time. The mineral-bearing solutions of various sorts formed the vast copper deposits of Bingham, Utah, of Morenci, Arizona, and of Santa Rita, New Mexico. The silver of Park City, Utah, as well as of the great Comstock lode, Tonopah, and other localities in Nevada, was similarly formed in middle and later Cenozoic time. The gold of many of the spectacular mining camps of the West, such as Goldfield, Nevada, and Cripple Creek in the Rockies, had a similar date of origin.

Mexico, Central America, Peru, and Bolivia also provide notable examples of the great mineral wealth we owe to the crustal disturbances and intrusive activity of the Cenozoic.

Diatomaceous Earth. Thick beds of pure diatom deposit are quarried from Miocene strata at Lompoc, California, and in Chesapeake Bay, for use chiefly as a sound- and heat-insulating material, as a base in polishing and scouring powders, and in various other ways. The output in 1939 was 105,000 tons, valued in excess of $2,000,000.

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The principle accepted by Dr. Longwell is that adopted, at his suggestion, in the previous edition of this book, which then led us to the conclusion that the cutting began after Pliocene time. Since then, critical restudy of the vertebrate fossils in the Muddy Creek formation (youngest of the interior basin deposits cut into by the Colorado River) indicates that its age may be as old as Miocene instead of Pliocene (as previously believed).

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Collateral Reading

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An up-to-date account of the modern physiographic features which were produced during Cenozoic time in the western United States.

Guide Book of the Western United States; by M. R. Campbell and others. U. S. Geological Survey, Bulletins 611–614, 1915. Part A, The Northern Pacific Route, with a Side Trip to Yellowstone Park; Part B, The Overland Route, with a Side Trip to Yellowstone Park; Part C, The Santa Fe Route, with a Side Trip to the Grand Canyon of the Colorado; Part D, The Shasta Route and Coast Line.

Written for the tourist who has an interest in geology. Maps and running comments on all geologic features of interest within view of the routes followed.

Chapter 18

ICE SCULPTURES THE FINAL SCENE

The Pleistocene Ice Ages. Glacier ice has recently covered approximately one-third of the land surface of the Earth. Its effects may be seen on every hand—in the serrate crests of mountains carved by valley glaciers, in the lake lands of Canada and Scandinavia, and in the drift plains of the north-central states and of north-central Europe. Over large parts of the Northern Hemisphere, human culture and industry have been profoundly influenced by this fact, for the glaciers stripped away the soil from some regions, made swamp lands of others, deposited coarse boulder till in places, and over large areas spread the materials of an uncommonly deep, rich soil. In such parts of the world, ice has given the final touches in the shaping of the modern landscape (Fig. 280).

In view of the far-reaching influence of glaciation during this last geologic epoch, the Pleistocene has picturesquely been called *The Ice Age*. Such a term, however, is a misnomer. It disregards the fact that there was not one ice age but four, and that together they comprised but a small part of Pleistocene time. In other respects this last epoch is closely allied to the Pliocene and earlier epochs of the era, and for that reason it was treated with the rest in the preceding chapter. The long interglacial ages differed in no important respects from the preceding ages of the Pliocene. Nevertheless, the glacial ages have such interest and importance that this special chapter is devoted to that one aspect of Pleistocene history.

Extent of the Glaciation

Distribution of Glacier Ice. Three major ice sheets were present in the Northern Hemisphere (Fig. 281). One of these, centered over Hudson Bay, occupied nearly all of Canada and spread southward into the United States (Fig. 282); another centered over Scandinavia and reached the plains of north Germany and western Russia; and the third occupied part of Siberia. Greenland was ice-capped then as now, and the Scandinavian Ice Sheet extended southward across the

FIG. 280. Economic and cultural effects of the Pleistocene glaciation in North America. The aerial view of the lake country of Manitoba (top) shows the effect of glacial scour which removed the mantle and scooped out lake basins in solid rock. The boulder field in New England (center) suggests how the clearing of the land was made a formidable task by coarse glacial drift. The wheatlands of the Red River Valley in the Dakotas (bottom) are part of the floor of glacial Lake Agassiz. Photographs from Royal Canadian Air Force, U. S. Geological Survey, and North Dakota Agricultural Experiment Station, respectively.

floor of the North Sea and covered all of the British Isles except the southern edge of England. In the Southern Hemisphere the Antarctic Continent undoubtedly was ice covered, and the highlands of Patagonia in South America and of South Island in New Zealand were heavily glaciated. In addition, nearly all the lofty mountains of the world were capped by snow, and valley glaciers reached far below the present snowline.

It is remarkable that the glacier ice covered great areas of lowland, and in central United States reached south of latitude 40° where, at present, summer temperatures of 100° F. are not rare and where the regional snowline is at least 6000 feet above sealevel.

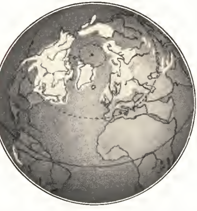


FIG. 281. Pleistocene ice fields of the Northern Hemisphere.

In the United States the higher parts of the Rocky Mountains were glaciated as far south as New Mexico (Fig. 282), and the Sierra Nevada and Cascade ranges were also ice covered. Glacier National Park in the Rockies and Yosemite Valley in the Sierra afford well-known illustrations of the work of these Pleistocene glaciers. The Alps, the Himalayas, the Caucasus, the Pamir, and other lofty ranges of Eurasia carried great snowfields from which valley glaciers pushed out beyond the foothills onto the plains. The higher parts of the Andes in South America also had extensive glaciers.

The directions of ice movement in North America are indicated in Fig. 282. These have been determined by mapping the end moraines, by plotting the direction of glacial striæ, and by noting the distribution in the drift of boulders of distinctive types of rock that could be traced back to their source. The striking fact is that the ice did not spread southward from the polar region but radiated from centers in the latitude of Hudson Bay.

Two quite distinct sheets can be distinguished, even though they formed parts of a single great field of ice. The larger of these is the *Laurentide Ice Sheet,*[1] which centered over Hudson Bay and thence spread southward for a distance of some 1600 miles across the Great Lakes region into the Mississippi Valley. It also spread westward up

Fig. 282. Pleistocene glacier ice in North America. Somewhat generalized to show maximum extent of the glaciation. Arrows show generalized directions of glacier flow. After Richard F. Flint.

the long slope of the High Plains to the foothills of the Rockies and northward to the Arctic islands. On the east and northeast the ice pushed out to sea and, at its maximum, may have been continuous with the Greenland Ice Sheet.

It is probable that the Laurentide glacier ice first began to form over the mountains of eastern Labrador and Baffin Island [1] and from there grew westward until the center of accumulation was in the Hudson Bay area.*

* The current belief that there were two independent centers of accumulation in this region, one west of Hudson Bay and another over Labrador, is not borne out by recent studies.[1]

The second major ice sheet was the *Cordilleran Glacier Complex*, which occupied the mountainous region of western Canada. Ice probably began to form here as valley glaciers that radiated from the highest parts of the Coast Ranges and the Rockies. As these rivers of ice were extended to the lowlands, they developed into a complex of piedmont glaciers that not only spread over the foothills east of the Rockies and into the sea west of the Coast Ranges, but also converged to fill the broad basin between the two mountain systems. Up to this time the high ranges, intercepting the moisture-bearing winds, had been the chief centers of accumulation, and the spread of ice had been in part centripetal. As the intermont basin was filled, however, it became the chief center of accumulation from which movement radiated over both the Coast Ranges and the Rockies.

Thickness of the Ice. There is no direct evidence of the thickness attained at the center of the Laurentide Ice Sheet. The area of this Pleistocene sheet (4,800,000 square miles) was somewhat greater than the existing ice cap of the Antarctic Continent (4,000,000 square miles). The surface of the ice in Greenland and on the Antarctic Continent is about 10,000 feet above sealevel and appears almost flat except near the periphery, where it slopes off with increasing steepness to the wasting margins. During maximum glaciation the ice of the Laurentide sheet flowed westward up the long slope to the foothills of the Rockies, where it reached an elevation of about 4000 feet, and in its southward flow it covered the White Mountains (exceeding 5000 feet) and probably all of the Adirondacks (exceeding 4000 feet). Since ice moves in the direction toward which its surface slopes down, the altitude at the center of accumulation must have exceeded by a considerable amount the height of these features which the ice overrode near its periphery. Since the surface of the land about Hudson Bay is near sealevel (and was then probably depressed by a thousand feet or more under the weight of the ice), it is not unlikely that the glacier was at least 8000 to 10,000 feet thick over a large area.

Glacial and Interglacial Ages

When erratic boulders strewn over the plains of northern Europe and over New England were recognized as the work of a former ice sheet, they were at first quite naturally attributed to a single glaciation. But as the study of the glacial deposits was carried westward into Illinois, Wisconsin, and Iowa, two distinct sheets of drift were

found at many places to be separated by old soil, beds of peat, or layers of till that had been leached and decayed (Fig. 283). Here the uppermost drift, like that in New England, appeared fresh, but the buried drift sheet showed the effect of chemical decay and was obviously much the older. Moreover, in places, the soil and peat or gravels between two such sheets of till included fossil wood and leaves and bones, indicating the existence of animals and plants of temperate

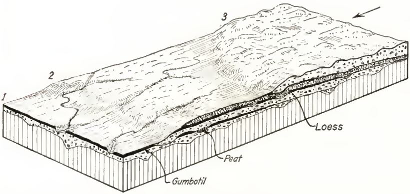


Fig. 283. Idealized block diagram showing the relations of three imbricating drift sheets. The block represents an area many miles across, and the vertical scale is exaggerated. The first glaciation spread till across the entire region. In the long interglacial age that followed, the surface of this first drift sheet was weathered to gumbotil (*black*). The second advance of the ice fell short of the first, and in a broad marginal belt the glacier ice overrode the older till, gumbotil, and peat deposits. During a second interglacial age this till in turn suffered long weathering and developed a gumbotil. In connection with the third glaciation, loess was spread widely over the older drift, and this in turn was overridden by the glacier ice which fell short of the middle of this area. No gumbotil has yet formed on the youngest till.

climate. On this basis it came to be realized, about 1870, that two distinct advances of the ice had been separated by a relatively long interval of warm climate when forests grew over the older drift, and plants, such as the pawpaw, ranged considerably north of their present limit.

By further application of the same principles, it was soon discovered that more than two glacial ages are recorded in the upper Mississippi Valley. Meanwhile, similar discoveries were made in northern Europe; and now four glacial and three interglacial ages are established in both Europe and America. These have been named for localities in which their deposits are typically developed, each glacial age in America bearing the name of a state. Independent names have

been used in Europe, but it now appears probable that the glacial ages recognized on the two sides of the Atlantic correspond in time.

Records of the last glacial age are so abundant and so ready of access that much detail can be worked out, and in recent years four distinct glacial advances, separated by extensive recession, have been recognized as subages of the last or Wisconsin glacial age.

Implications of Pollen Analyses. An analysis of the pollen, abundantly preserved in peat associated with the glacial deposits, has recently added much to our understanding of the glacial history. Since the pollen of each kind of forest tree is distinctive, a pollen analysis indicates quite clearly the composition of the surrounding vegetation in which any deposit of peat accumulated. The modern species were extant during the whole of the Pleistocene and, then as now, were grouped into characteristic assemblages—for example, tundra plants, fir-spruce forest, tamarack, pine-mixed hardwood forest—each adapted to a distinct climatic environment. Thus it is possible to infer, for example, that when certain interglacial deposits were forming at Toronto (the Don beds) the mean temperature was higher by 2° or 3° C. than it is at present, and conversely, that when certain layers of peat were forming about Quincy, Illinois, the surrounding forests were of balsam fir, tamarack, pine, and birch, an assemblage that now lives at least 200 or 300 miles farther north.

Implications of Fossil Mammals. The land animals of both Europe and North America likewise migrated widely as the ice spread and waned. During the height of glaciation, for example, the reindeer came as far south as southern New England, and the musk-ox ranged to Kentucky and Arkansas and Texas. On the other hand, some of the interglacial deposits include both animals and plants that suggest a climate somewhat warmer than the present.

It is clear, therefore, that the climate was colder than at present during the four glacial ages when ice covered far more than half of North America and approximately half of Europe, and that it was somewhat warmer than at present during at least some parts of the interglacial ages, and that the ice sheets then had retreated far to the north and probably had disappeared both from the mainland of North America and from Europe.

Stratigraphy of the Drift

The time represented by the existence of one of the continental ice sheets described above is a *glacial age,* and the time that elapsed be-

tween two of these is an *interglacial age*. These are the major *time* units of the glacial epoch, and the corresponding stratigraphic unit is a *stage*. Thus, the deposits formed during the Wisconsin glacial age constitute the *Wisconsin stage*, and those formed during the Sangamon interglacial age constitute the *Sangamon stage*.

Figure 284 shows the distribution of the four drift sheets. Their stratigraphic relations are further illustrated by Figs. 283 and 285.

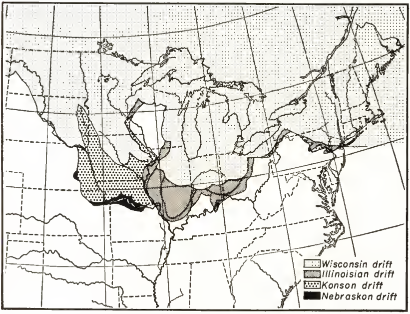


FIG. 284. Map showing the southern limit of glacial drift in the United States. Note that in the Mississippi Valley the older drift sheets extend farther south than the youngest, and here four sheets are differentiated. After Richard F. Flint.

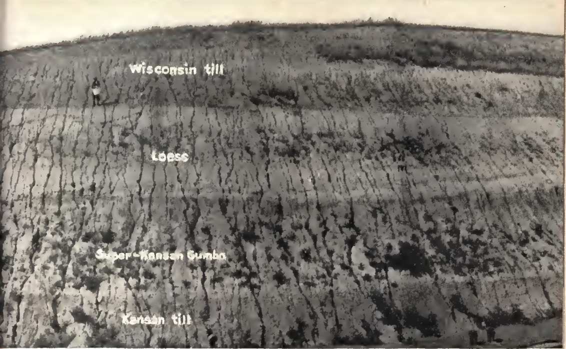
The *Wisconsin stage* is the uppermost drift sheet and is the one most easily mapped and the best understood. For this reason it will be described first, and the older sheets will follow in turn, thus reversing the actual historical sequence. The end moraines of the Wisconsin stage loop across the Central Lowland in festoons that outline the great southern lobes of the ice. Its surface still retains the characteristic features of a glacial deposit—the swells and swales of the end moraines and the broad undulations and lakes and swamps of the ground moraine, locally diversified by drumlins. It has suffered only slight chemical change during the few thousands of years since the

ice wasted away. Although a thin soil has formed over it and peat has accumulated extensively in the lakes and swales, chemical decay, even in fine materials, is limited to slight leaching to an average depth of 2 or 3 feet, and most of the boulders are as fresh as quarried stone. Along the main streams it has been partly removed, but elsewhere it has undergone but slight erosion. Outwash plains and valley trains beyond the end moraines are still easily recognized.

In New England the Wisconsin ice sheet flowed out beyond the present coastline (then dry land), largely destroying or concealing any marks of earlier glaciation, and there glacial studies are concerned almost exclusively with the Wisconsin drift. In the lowlands of the Ohio-Missouri River basins, on the contrary, the Wisconsin ice fell short of the earlier advances, and there the several known Pleistocene stages form an imbricated succession, as suggested in Fig. 283, and each in turn can be studied.

The *Illinoian stage* is known chiefly in Illinois, southern Indiana, and central Ohio, where it is not covered by Wisconsin drift, but it is exposed also in smaller areas in Wisconsin and Pennsylvania and New Jersey. Unlike the Wisconsin till, which is largely composed of sand, gravel, and boulders, the Illinoian till is chiefly made of silt and clay. Its surface retains traces of morainic topography, but mass-wasting of swells and deposition in swales have softened the relief.

Overlying the Illinoian till are materials that must be referred to the third interglacial (Sangamon) stage. These include the leached and decayed zone at the top of the till, numerous deposits of peat and of stratified sand and gravel, and a sheet of loess. In contrast to the freshness of the Wisconsin drift, the Illinoian till has a zone of oxidation that extends from 10 to 25 feet deep and a zone of gumbotil averaging 4 feet thick, even where it is overlain by fresh Wisconsin drift. *Gumbotil* is a dark sticky subsoil so named because it is a product of the chemical weathering of till. The presence of such material under the Wisconsin drift, where it has been protected since the beginning of the Wisconsin age, proves, of course, that the chemical decay was experienced by the Illinoian till during the Sangamon interglacial age. Also belonging to this last interglacial age is a widespread layer of loess (the Loveland loess of Nebraska and the Sangamon of Illinois). Pollen in a bed of peat preserved at Wapello, Iowa, records vegetation identical with that now inhabiting the area, suggesting that while this peat was forming the climate in Iowa was like the present.



GEORGE F. KAY.

Fig. 285. Superposed sheets of till with gumbotil and loess exposed in a railroad cut southwest of Rhodes, Iowa. The scale is indicated by the man at the left above.

The *Kansan stage* is represented by a sheet of till that is widely exposed in Iowa, northern Missouri, and northeastern Kansas, where it averages about 50 feet in thickness. East of the Mississippi River it is known in places beneath the younger sheets of drift.

During the second interglacial (Yarmouth) age, the surface of the Kansan till was deeply leached and decayed, and a layer of gumbotil was formed with an average thickness of 11 feet. In places the till is covered with gravel beds, representing outwash, that are so deeply decayed that granite boulders commonly crumble and fall to pieces when struck with a hammer. The Kansan till is also widely covered with a layer of loess (Fig. 285). Beds of peat found at several places between the Kansan and Illinoian tills have yielded the pollen of forests of balsam fi., pine, and tamarack, suggesting a climate somewhat cooler than the present. It is not known, however, what part of the long interglacial age they represent.

The *Nebraskan* drift had approximately the same distribution as the Kansan, and its exposures are very limited, but it lies buried be-

neath most of the area mapped as Kansan. It was a thick sheet of till spread over an irregularly eroded preglacial surface and averaging more than 100 feet in thickness.

Overlying the Nebraskan till are deposits of the first interglacial (Aftonian) stage. These include a layer of gumbotil averaging 8 feet thick, and scattered deposits of peat sandwiched between Nebraskan and Kansan till. Pollen analyses from five such deposits in Iowa indicate at first a long time when the region was occupied by conifer forests, suggesting climate cooler than the present, then a landscape covered with grasses, indicating long endurance of a climate like the present, and finally a return of conifer forests and cooler climate as the Kansan glacial age approached.

Duration of the Ice Ages

Much ingenuity has been devoted to attempts to establish an absolute time scale for this last geologic epoch, one in which events could be dated in years. Current results are indicated in the table on p. 451, but it must be confessed that the age calculations involve a large degree of probable error and in part are highly subjective. Such figures are, therefore, only tentative estimates.

Estimates of Postglacial Time. Nearly all attempts to measure the length of Pleistocene time involve two steps: first, measuring the length of "postglacial" time and, second, with this as a yardstick, estimating the relative length of each of the interglacial ages. Two chief criteria have been invoked to measure "postglacial" time, one the rate of recession of postglacial waterfalls and the other the bodies of varved silt and clay formed in proglacial lakes during the recession of the last ice sheet.

The Falls of St. Anthony in the Mississippi River at Minneapolis will serve to illustrate the first method of calculation. Below the falls, and extending nearly 7 miles to Fort Snelling, there is a gorge 75 to 100 feet deep and about a quarter of a mile wide, produced by the recession of the falls. It can be demonstrated that the cutting of this gorge began when the ice margin, during the last deglaciation, stood near the position indicated in Fig. 286. In nearly 250 years after the falls were first observed by white men, their recession upstream averaged 2.44 feet per year. At this rate, 15,000 years were required to cut the postglacial gorge.

There is good reason for believing that the cutting of this gorge began at about the stage of deglaciation represented in Fig. 286. In

Fig. 286. St. Anthony Falls and their postglacial history, showing position of the ice front and regional drainage relations as they existed when the cutting of the gorge below the falls began. Details of the area about the falls are shown in the inset, in which buried preglacial channels are indicated in white and modern valleys in dark gray. Based on data from Leverett and Taylor and from G. M. Schwartz.

preglacial time the Mississippi had cut a wide valley, its main trunk following approximately the course of the present Minnesota River above Fort Snelling. The last glaciation filled all preglacial valleys with drift, and, when the ice melted back, the streams at first wandered over the surface of the drift, eventually incising themselves in new valleys. As Minnesota was exposed, three main streams, the St. Croix, the upper Mississippi, and the Minnesota, united near St. Paul. Cutting down through the drift, the trunk stream discovered the old preglacial valley just below St. Paul (see inset of Fig. 286) and proceeded to remove the loose fill below this point with relative ease. But from St. Paul to a point just south of Fort Snelling the new stream was superposed upon the old upland of horizontal limestone beds. Here its downcutting was greatly retarded, and, as it plunged from the surface of the limestone into the old valley, a falls was initiated that gradually migrated upstream until it again cut through into the buried preglacial valley a short distance southwest of Fort Snelling. The recession of this great falls produced the narrows in the valley at St. Paul, which are therefore obviously postglacial.

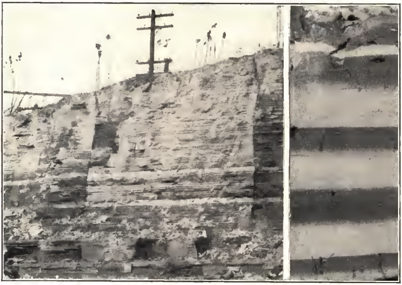
For a time after deglaciation of the region around Minneapolis, all three stream branches carried great volumes of meltwater, but after the ice margin had reached the Canadian border, the drainage through the upper Mississippi diminished to something like its present volume. That of the Minnesota River, on the contrary, increased greatly as it became the outlet of the vast glacial Lake Agassiz, which formed over the Red River Valley while the ice still prevented drainage to the north. Thus, until the disappearance of Lake Agassiz, the stream we now know as the upper Mississippi was but a second-rate tributary to a great glacial stream that followed the present valley of the Minnesota River above St. Paul. The cutting of the narrows at St. Paul was chiefly the work of this great glacial stream and was accomplished while Lake Agassiz was discharging the meltwater from a great area of the ice. This gives us the clue to the position of the ice margin when the postglacial narrows at St. Paul were cut.

After the great falls in the glacial Minnesota River had receded past the mouth of the Mississippi tributary, the latter plunged from its limestone bed into the new valley and thus initiated the Falls of St. Anthony.

Unhappily for this calculation, however, a comparison of maps, sketches, and descriptions made since 1680 shows that the rate of recession has accelerated greatly during the period of observation. This is probably due to the fact that the Plattville limestone, which holds up the lip of the falls, thins upstream in the vicinity of the present falls. It appears evident, then, that the average rate of recession has been less than 2.44 feet per year, that the cutting of the gorge may have required more than 15,000 years, and that the probable error in the rate of recession may be great. Furthermore, we have been attempting merely to measure the length of time since the ice front stood at the position indicated in Fig. 286. It had already retreated some 700 miles from its farthest advance in Iowa, and there is no objective basis for determining the time involved in that retreat. A figure of 10,000 years has been postulated, making the total time 25,000 years since the ice front was in Iowa, but 10,000 years is a highly subjective inference.

A quite different approach to the measurement of postglacial time involves the study of varved silt and clay. The strikingly banded appearance of such deposits (Fig. 287) is due to a regular alternation of thin laminæ of silt (normally light in color) and of fine clay (normally darker). The Swedish geologist DeGeer discovered that such lamination is due to the special conditions that exist in proglacial

lakes. During the summer months meltwater bears fine sediment in suspension, giving the water a milky, turbid appearance. Currents and waves spread this turbid water, from which the coarser particles gradually settle to form a layer of silt on the lake floor. When winter comes, the meltwater ceases to flow and the lake freezes over. Then for some months, while the water is free of disturbance, even the col-



R. F. Flint.

FIG. 287. Varve clay from a glacial lake bed at South Hadley, Massachusetts. At the right, a small detail, natural size, showing the gradation of the light gray, summer layers upward into the dark, winter layers.

loidal particles of sediment settle slowly to form a layer of fine unctuous clay. With the return of summer a new layer of silt forms over the previous winter's deposit. Thus the paired layers of silt and clay, like growth rings in trees, record actual years of time, and it is a simple matter to count the layers and determine how many years were required for the formation of a deposit of varve clay.

Of course, no single proglacial lake existed throughout the time involved in the shrinkage of the ice sheet, but DeGeer discovered an ingenious way of matching the bands in contemporaneous deposits of different lakes or in different outcrops, and thus was able to piece together many of the fragments of the record. Lakes tend to form about the margins of a melting ice sheet, occupying either depressions

behind moraines or inequalities in the rock floor where the ground moraine is thin, and thus probably much of the time represented by deglaciation was recorded in varved sediments in one place or another. DeGeer pieced together the records of about 1500 outcrops lying between the southern tip of the Scandinavian peninsula and the modern proglacial lakes in central Sweden, and on this basis inferred that the shrinking ice exposed southern Sweden about 13,500 years ago. The ice margin lay in the plains of southern Germany during the maximum glaciation, and it has been impossible to find varved deposits to measure the duration of the recession from that limit to southern Sweden, but obviously it was several thousands of years. Recent estimates, based in part on DeGeer's work, place the date of maximum expansion of the last glaciation in Europe at about 35,000 years ago, but such estimates rest on no objective data and are obviously little more than guesses.

As a result of various attempts at such calculation, it is now commonly assumed that about 25,000 years have elapsed since the last (Mankato) advance of the Wisconsin Ice Sheet. This is probably of the right order of magnitude but can lay no claim to accuracy.

Estimates of a Pleistocene Time Scale. There is no direct method of determining the length of the interglacial ages, and estimates of their duration are based upon a comparison of the weathering and decay of the older tills. For example, the Wisconsin till is almost fresh, showing but slight leaching in the upper 2 or 3 feet, whereas the Illinoian is deeply leached and has developed a gumbotil about 5 feet thick. It is certain that this long decay took place before the Wisconsin glaciation, because the last sheet of till has protected the buried drift from weathering. Obviously the Sangamon interglacial age was several times longer than all postglacial time. The Kansan drift is even more deeply weathered, and its gumbotil is about 11 feet thick. Its boulders also have been weakened by long decay. The underlying Nebraskan drift has a somewhat thinner gumbotil, and the first interglacial age was somewhat shorter than the second. Although there is no dependable criterion for the comparison, it is the judgment of the most profound students of glacial deposits that the Sangamon interval was not less than five times the length of the postglacial age, the Yarmouth not less than twelve times, and the Aftonian about eight times. The resulting estimates are 135,000, 310,000, and 200,000 years, respectively. To these must be added the quite uncertain duration of the several glacial ages, giving a total duration for the Pleistocene epoch estimated roughly at a million years. There

is now hope that a study of the radium concentration in sediments on the sea floor will give us an absolute chronology for the last 300,000 years or so.[2]

Current estimates of glacial dates are indicated in the following table of Pleistocene chronology by Flint.

CALENDAR OF PLEISTOCENE TIME

Epochs (of Time) Series (of Deposits)	Ages (of Time) Stages (of Deposits)	Subages (of Time) Substages (of Deposits)	Duration in Years (Estimates in Roman type; guesses in *italics*)	Estimated Time Elapsed to Present
Pleistocene epoch	Wisconsin Glacial	Mankato Cary Tazewell Iowan	25,000 10,000 10,000 10,000	25,000 35,000 45,000 55,000
	Sangamon Interglacial		135,000	190,000
	Illinoian Glacial		*100,000*	290,000
	Yarmouth Interglacial		310,000	600,000
	Kansan Glacial		*100,000*	700,000
	Aftonian Interglacial		200,000	900,000
	Nebraskan Glacial		*100,000*	1,000,000
Pliocene epoch				

Fluctuations of Sealevel. If the modern ice sheets of Greenland and the Antarctic Continent were melted, sealevel would rise, it is estimated, by as much as 100 feet, drowning the low coastal plains and transforming the lower courses of many streams into estuaries. But if, on the contrary, the former great Pleistocene ice sheets were restored, the water thus withdrawn from the oceans and piled up on the lands would lower sealevel by 300 feet or more, shifting the shoreline seaward almost to the present 50-fathom line.

There is clear evidence that such striking fluctuations of sealevel have taken place repeatedly since the beginning of the Pleistocene. During times of maximum glaciation, streams were extended across the exposed parts of the continental shelves, cutting valleys that are now submerged. In subtropical regions the reduced temperatures at the same time inhibited the growth of corals and permitted the waves to cut wide benches about oceanic islands and along exposed coasts. These benches have since been transformed into lagoons by the growth of barrier reefs along their margins as the sealevel rose. Some of the low wave-cut benches extensively preserved along the modern coasts may have been cut during interglacial ages when the ice sheets of Greenland and the Antarctic Continent were reduced and the sealevel stood higher than now.

The lowering of sealevel by 300 feet or more made dry land out of extensive areas of shallow sea and permitted migrations of land animals and plants that would now be impossible. England, for example, was united to the continent of Europe, so that the hippopotamus crossed the channel from France, and Borneo and Sumatra in the East Indies were a part of Asia, so that elephants, rhinoceroses, and other large mammals crossed the lowlands now submerged to form the floor of the Java and Sunda seas. Alaska and Siberia were also united by land, and the woolly mammoth crossed freely.

Depression of the Ice-Covered Regions. The ice caps that formed over Canada and Scandinavia were loads too great for the Earth's crust to support, and both regions sagged to the extent of many hundreds of feet at the very least. The depression was greatest where the ice was thickest, and in Canada it amounted to about a thousand feet in the area midway between the Great Lakes and James Bay. Since the ice wasted away, there has been substantial recovery, but before the upwarping took place, unmistakable records of the depression had been made in the form of beach ridges and wave-cut cliffs along the shores of vast proglacial lakes. These features, still recognizable, have been studied and mapped. One of them, marking the shore of glacial Lake Algonquin, is at an elevation of nearly 600 feet in west-central Michigan but rises to 935 feet at Sault Ste. Marie, 1150 feet at North Bay on Lake Huron, and apparently 1450 or 1500 feet at Goudreau Lake, 150 miles north of Sault Ste. Marie. This indicates a relative upwarp in postglacial time of 335, 550, and 850–900 feet, respectively, at the places named. The beaches of glacial Lake Agassiz (Fig. 286) in Manitoba show a similar upwarp toward the north amounting to at least 400 feet.

When the ice had wasted back far enough to free the St. Lawrence Valley, the region was still so much depressed that marine water spread up the St. Lawrence and into the Champlain Valley and probably into Lake Ontario, depositing a layer of blue clay with abundant shells of an arctic molluscan fauna. This is the *Leda clay,* so called for a small but characteristic clam. The recent discovery of two whale skeletons in bogs above the glacial deposits in Michigan indicates that for a brief time the sea was directly connected with the Pleistocene Great Lakes. Marine shells and the bones of whales have been found in the Leda clays at least 500 feet above sealevel at the Vermont-Quebec boundary, nearly but not quite up to the Lake Ontario level at Kingston, and at about 600 feet in the Montreal-Quebec area. The postglacial upwarp thus indicated is probably a minimum measure of the depression caused by the ice.

Glacial Erosion beneath the Ice Sheets. Radial movement of the Laurentide Ice Sheet stripped the mantle from a vast area of the Canadian Shield, leaving a floor of fresh bedrock scoured unevenly into thousands of shallow basins now occupied by lakes (Fig. 280). The areas of bare rock showing through the scant cover of vegetation advertise the fact that the glaciation cost eastern Canada one of her greatest resources, the soil that had formed during the ages before the coming of the ice.

Over a broad peripheral belt the ice spread its load of drift, filling pre-existing valleys with till, and smoothing the inequalities of the surface. Thus the material stripped wholesale from the southern part of Canada was spread widely over the north-central United States to form the source of a very deep rich soil.

Drainage Changes. As the ice sheets advanced southward into the United States, all north-flowing streams were blocked, and the meltwater was turned along the margin of the ice until it spilled over divides into south-flowing streams. The channels thus formed at the maximum advance were in many places held after the disappearance of the ice, because former channels were obliterated by the drift. The present course of the Ohio River is due, thus, to the welding together of many short tributaries to different streams, several of which had flowed northward in preglacial times (Fig. 288). The course of the Missouri was also locally shifted to the southwest. For this reason the Ohio and Missouri rivers record rather closely the limits attained by the ice sheets at their greatest extent.

Development of the Great Lakes. Before the glaciations the basins now occupied by the Great Lakes were probably broad lowlands

eroded by preglacial streams. The Lake Superior basin marks an ancient synclinal structure occupied by relatively weak rocks in which a broad valley had been eroded; the other lake basins were carved on the outcrops of relatively weak rocks in front of or between the cuestas that had been sculptured by Cenozoic erosion of the Paleozoic formations overlapping on the Canadian Shield. These lowlands were

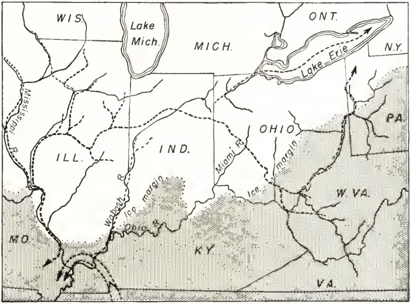


FIG. 288. Drainage changes in the Ohio and Mississippi river basins due to glaciation. Preglacial drainage courses are shown in broken lines. Adapted from R. F. Flint (1947).

drained by streams, some of which probably flowed southward through gaps in the cuestas, while others may have flowed northeastward into the St. Lawrence. As the successive ice sheets flowed outward, they filled these lowlands with thick ice lobes that gouged and deepened them, especially where, as in the case of Lakes Superior and Michigan, the axis of the depression nearly coincided with the directions of ice flow.

South of the Great Lakes basins, on the other hand, the ice sheets spread a thick mantle of drift that filled and deeply buried the old valleys for scores of miles. As a result, when the ice later retreated northward over the Great Lakes region, its front became deeply lobate, with a great tongue of ice occupying each of the deepened basins.

FIG. 289. Three stages in the development of the Great Lakes as the last ice sheets wasted away. Adapted from Leverett and Taylor, U. S. Geological Survey.

As these shrank back, lakes formed about the end of each of the lobes, the water standing at the level of the lowest spillway that would lead southward across the drift into the Mississippi drainage system. At first the overflow was southward via both the Wabash and Illinois rivers, but somewhat later it was westward along the front of the ice to the vicinity of Chicago (Fig. 289*A*), where an outlet was found via the Illinois River. Eventually the Mohawk Valley in New York was freed of ice, and this opened a much lower spillway whereby the drainage was for a time diverted east into the Hudson River (Fig. 289*B*). At a still later stage the St. Lawrence Valley was opened, and the drainage of the upper Great Lakes escaped northeast from the Lake Huron basin across southern Ontario by way of the Ottawa Valley (Fig. 289*C*). As the ice wasted away, there was gradual recovery from the depression it had caused, resulting in progressive upwarp of the region northeast of a hinge line that ran through central Michigan and southern Ontario (Fig. 289). This ultimately raised the Ottawa outlet until the lowest spillway was across the edge of Niagara cuesta at Lewiston. At this stage, the Niagara River increased greatly in size.

Various other important lakes were formed by the glaciation. The Finger Lakes of central New York, for example, mark open valleys carved in the margin of the Allegheny Plateau by northward-flowing streams in preglacial times. As the ice rode southward, it gouged deeply where it was crowded into these narrow valleys. Upon the retreat of the ice, these overdeepened places became lakes. The greatest of all the glacial lakes was *Lake Agassiz,* previously mentioned (Fig. 286), which formed in the plains of eastern North Dakota, northwestern Minnesota, and Manitoba, while the ice still occupied the basin of Hudson Bay, imponding the water until it overflowed the divide to the south by way of the Minnesota River. Although the lake attained an area nearly five times as great as that of Lake Superior, it was relatively shallow, the old strandlines indicating a probable maximum depth of about 400 feet at the international boundary. The disappearance of the ice allowed the lake to drain away into Hudson Bay. The floor of the former Lake Agassiz is now the remarkably flat and fertile wheat land of North Dakota and the Red River Valley of Manitoba (Fig. 280).

End of the Ice Ages

If our time scale for the Pleistocene epoch in any sense approaches reality, it is clear that we probably are now in a minor interglacial

subage in which the icefields have shrunk from a maximum of 32 per cent of the area of the land surface of the Earth to about 10 per cent. There are still more than 5,000,000 square miles of ice sheets in the Antarctic Continent and Greenland, and the polar seas are choked with floe ice, while lofty mountains the world around bear active glaciers. Furthermore, it is estimated that a decline in the mean annual temperature of not more than 5° C. would bring a return of the ice sheets as they were during the last advance.[1]

Judged by every criterion we know, the interglacial ages vastly exceeded the time that has elapsed since the last ice sheets began to wane; and fossils preserved between the drift sheets prove beyond doubt that the climate at times during those interglacial ages was appreciably warmer than it is now. Furthermore, there is clear evidence that postglacial world climates reached a maximum of warmth between 6000 and 4000 years ago and since then, with minor oscillation, have become cooler and more moist down to the present time. Whether the ice sheets will spread again or will disappear completely during the next few thousands of years, it is quite impossible to judge; but clearly the *Present* is only an age in the Pleistocene epoch.

Meanwhile the sword of Damocles hangs over us. If the ice sheets should again spread to the limits they occupied a few thousands of years ago, mass migrations would occur on a scale without precedent in the history of mankind, for the densely populated centers of Europe and the United States, to say nothing of all Canada, would slowly become uninhabitable. And if, on the contrary, the climate should return to its geologic norm and the last of the ice sheets should disappear, the meltwater would raise sealevel by 70 to 100 feet, slowly submerging all the great seaport cities of the world. In any event, the changes will come too slowly to concern anyone now living, but they may profoundly shape the destiny of civilization within the next few thousands of years.

We can only guess when the end of the Ice Ages will come, as we contemplate some of the problems it will entail for mankind!

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This comprehensive and entertainingly written volume was an invaluable source in the preparation of this chapter.

[2] *Time Relations in Ocean Sediments;* by C. S. Piggot and W. D. Urry. Bulletin of the Geological Society of America, Vol. 53, 1942, pp. 1187–1210.

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YALE PEABODY MUSEUM.

Fig. 290. Skeleton of the modern hedgehog, a persistently primitive and generalized mammal. About 2/5 natural size.

Chapter 19

MAMMALS INHERIT THE EARTH

With the extinction of the dinosaurs at the end of the Mesozoic, the way was open for the mammals to begin their conquest of the world. Although small and unimpressive at first, they evolved rapidly and soon eclipsed all other forms of animal life, so that the Cenozoic has well been called *The Age of Mammals.*

Trends of Mammalian Evolution

Comparative study of early Cenozoic fossils clearly indicates that the first mammals resembled the modern hedgehog (Fig. 290) in the following respects: (1) they were small; (2) they were short-legged and walked on the soles of the feet; (3) they had five toes on each foot; (4) they had forty-four teeth of which all but the canines were short-crowned; (5) their brains were small and their intelligence was of a low order; (6) they were long-faced, the jaws exceeding the brain-

case in size. Unlike the hedgehog, however, they had a long tail. From ancestors of this sort all the modern orders of mammals evolved. In this development four major trends can be detected in most of the groups.

First, there was a marked *increase in size*. The first mammals were small, and every group of large mammals can be traced back to small ancestors in the early Cenozoic rocks. The Eocene ancestor of the horse, for example, was not larger than a fox, that of the camel not bigger than a jack rabbit, and that of the elephant not greater than a large hog. The Eocene forebears of man, likewise, were the size of squirrels!

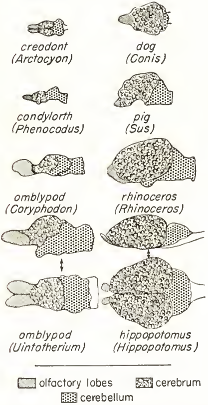

Fig. 291. Brains of archaic mammals (left) and of modern mammals (right) paired so that brains of animals having equal body size are side by side. Adapted from H. F. Osborn.

A second advance was in *brain power*. This involved not merely a larger brain but an increase in ratio of brain to body weight. The latter is graphically shown in Fig. 291, in which the brain of an ancient mammal (on the left) is paired against that of a modern mammal of the same size. The striking fact is that the greater size of the modern brain is in each case due to increase in the cerebrum, which is the seat of memory and reason. However, advance in brain power has been unequal in the several orders. At one extreme stand the insectivores (for example, shrews, hedgehogs, and moles) which have improved but little and have survived as stupid, retiring creatures; and at the other extreme stand the highest primates, with skulls distended by gray matter, capable of pondering the mysteries of time and space, and of harnessing atomic energy!

A third specialization concerned the *teeth*. In the primitive placental mammal the cheek teeth had sharp piercing or shearing cusps

but the crown was low, and the tooth quickly attained its full growth. Some, like the insectivores, chose a diet of insects and other such delicate morsels, and these have retained primitive teeth. Others with an omnivorous diet, like the swine, the bear, and man, have developed low blunt cusps. Carnivores, on the contrary, have narrow shearing cheek teeth for cutting, and greatly enlarged canines for holding and

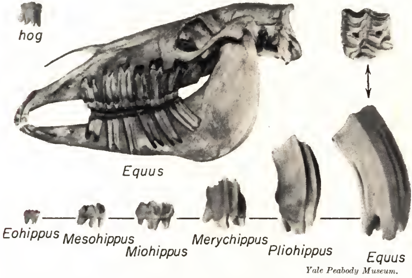

FIG. 292. Low-crowned and high-crowned cheek teeth. Top left, molar tooth of a hog in which the crown is shorter than the roots; right, corresponding tooth of a modern horse, *Equus*, in which the crown is about 5 times as long as the roots. Center, skull of the horse ($\times \frac{1}{6}$) dissected to show the high-crowned cheek teeth in place. Lower row, corresponding upper left molars of fossil horses from *Eohippus* to *Equus*, all at a uniform scale (about $\frac{1}{2}$ natural size). The crown is low in *Eohippus*, *Mesohippus*, and *Miohippus*, then increases rapidly in height from *Merychippus* to *Equus*. The crown view of the worn tooth shows the ridges formed of the enfolded enamel. The skull was dissected by S. H. Chubb.

tearing flesh. The most remarkable specialization is seen, however, in the grazing animals of the prairies, whose teeth must resist the wear of the harsh and commonly dusty grasses and must maintain a rough grinding surface. In these the cheek teeth become large and high-crowned and continue to grow throughout life (Fig. 292). Furthermore, the enamel is deeply enfolded into the crown, so that even after wear it forms sharp ridges, thus maintaining a good grinding surface. Each order has a distinctive pattern of enfolded enamel, making it almost as easy to identify the order of a fossil mammal by a single jaw tooth as by a whole skeleton (Fig. 293).

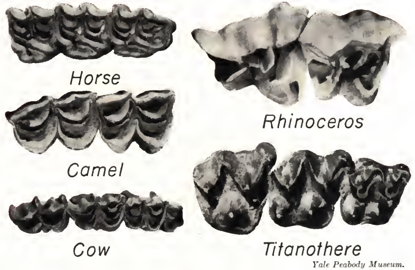

FIG. 293. Crown view of left upper molar teeth of horse, camel, cow, rhinoceros, and titanothere, to show the distinctive patterns of the enamel folds. (All on the same scale, about $\times \frac{1}{2}$.)

A fourth trend of evolution lay in *specialization of the feet*. Primitively the feet were short, and the animal walked flat on the soles with the heels touching the ground (Fig. 290); but during the ages marked specialization occurred according to environment and habits. Tree-dwelling types, like the monkeys and squirrels, developed prehensile hands with opposable thumb and great toe; carnivores evolved claws to seize and hold struggling prey; and the herbivorous animals of the plains, dependent for safety on fleetness of foot, underwent a remarkable specialization involving a rise onto the very ends of their toes, the development of hoofs, and a reduction and loss of some or all of the side toes.

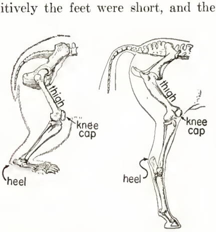

FIG. 294. Hind limbs of bear (left) and horse, showing correspondence of parts.

In swift running, an animal tends to rise up on its toes to attain a longer stride, and those that are endowed with long slender limbs have a natural advantage. In the struggle for existence, therefore, many of the plains animals were subjected to an age-long selection in which a great premium was placed on longer limbs and the ability to remain on the toes. The ultimate result is illustrated by the limb of a modern horse, contrasted with the unspecialized limb of a bear (Fig. 294). Above the heel there is little difference in size and proportions, the greater height of the horse being due to the elongation of the foot and to the fact that he stands on the very end of the toe with the heel far above the ground. This affords a great stride and leaves the powerful leg muscles bunched near the body where they can swing the slender extremity of the limb without sharing in its motion. The hoof developed, of course, as a protective armor for the tip of the toe.

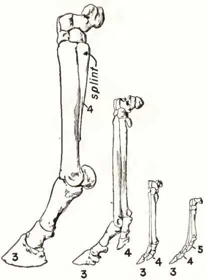

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FIG. 295. Loss of lateral digits in the horse. From right to left, the lower fore limbs of *Eohippus* of the Eocene epoch, *Mesohippus* of the Oligocene, *Merychippus* of the Miocene, and *Equus*, the modern horse. Corresponding digits bear the same numbers throughout.

Since the middle toes of a mammal are primitively and normally longer than the side toes, a rise to the ends of the digits lifts the side toes off the ground and leaves them dangling. In this condition they tend to degenerate and disappear (Fig. 295). In the odd-toed, hoofed mammals (Order Perissodactyla), the axis of the foot lies in the middle digit and, in the reduction, digits 1 and 5, as a rule, disappeared, leaving a three-toed foot. Heavy-bodied types such as the rhinoceros did not proceed further in this direction, but in the horse, digits 2 and 4 were reduced to mere vestiges (Fig. 38, p. 64, and Fig. 295), leaving a one-toed foot. In the cloven-hoofed mammals (Order Artiodactyla), the axis of the foot lies between digits 3 and 4. In this group, digit 1 was lost at a very early stage, producing a four-toed foot, such as is retained in the hog. Further specialization led to the

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Fig. 296. Restoration of Phenacodus, a condylarth from the Paleocene of Wyoming. The grasslike vegetation consists of sedges, not true grasses. From a painting by Charles R. Knight.

simultaneous reduction and loss of digits 2 and 5, and the production of a two-toed foot, such as that of the cattle, the deer, and the camel.

The Paleocene Vanguard

At the beginning of Cenozoic time, the mammals expanded like a race delivered from bondage. Although only three orders are recorded from Cretaceous rocks, fourteen are now known from the Paleocene series.[1] Notable among these are the *multituberculates, marsupials,* and *insectivores* that survived from the Cretaceous, and the *primates, rodents, carnivores, condylarths,* and *amblypods* that first appeared with the Paleocene. Nearly all these early mammals were small, few of them exceeding a large hog in size.

The *multituberculates* (Fig. 298) were small gnawing plant feeders superficially resembling a ground hog, but their cheek teeth were large

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Fig. 297. Restoration of Coryphodon, an amblypod from the lower Eocene of Wyoming. From a painting by Charles R. Knight.

and bore numerous cusps or tubercles, whence the name Multituberculata.

The *marsupials* were essentially like the modern opossum and at this time were possibly world wide in distribution. Outside of Australia and South America, however, they have never competed successfully with more progressive types and have never risen above the modest and retiring role played by the living opossum.

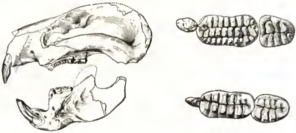
Insectivores were likewise small and much like the modern shrew and hedgehog. They appear to be the ancestral stock from which the other groups of placentals evolved, but the insectivores themselves did not share in that evolutionary advance.

Rodents include the modern gnawers, such as mice and rats and squirrels. The oldest representative of this order was found in the Paleocene beds of Montana in 1937.

Primates are represented in the Paleocene by small half-apes (tarsioids and lemurs) scarcely larger than squirrels.

Creodonts were precursors of the modern carnivores. Even in Paleocene time they showed considerable specialization, some being doglike and others catlike. Some had shearing teeth and sharp claws; others strangely blunt teeth and flattened toenails. Their brains, however, were less than half as big as those of modern carnivores of equal stature, and they must have been stupid brutes (Fig. 308).

The *condylarths* and *amblypods* (primitive ungulates) were the dominant orders of herbivorous animals during Paleocene time. The

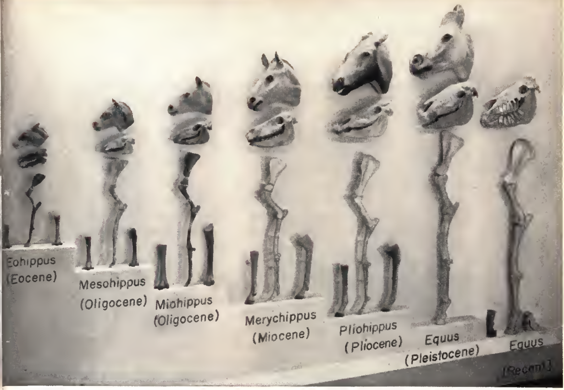


Granger and Simpson.

FIG. 298. A Paleocene multituberculate, *Tæniolabis*, from New Mexico. Side view of skull ($\times\frac{1}{4}$) and crown view of upper and lower left cheek teeth (enlarged).

condylarths were lightbodied and relatively agile; the amblypods stocky and ponderous. *Phenacodus* (Fig. 296) was a typical condylarth. The slender body, arched back, long tail, and short, five-toed feet give it a superficial resemblance to the carnivores; but each toe bore a small hoof, and its teeth were clearly those of a plant feeder. The brain was relatively small, and the teeth primitive and low-crowned. The condylarths appeared early in the Paleocene and ranged upward to the middle of the Eocene epoch, when they were replaced by the more advanced ungulates.

Coryphodon (Fig. 297), a typical Paleocene amblypod, was about waist-high to a man. It was thickset and had stout legs and blunt, five-toed feet, each toe bearing a hooflike nail. The canine teeth were tusklike, but the cheek teeth were relatively small and low-crowned. The amblypods appeared early in the Paleocene and ranged through to the close of the Eocene epoch. The earliest forms were scarcely larger than a sheep, but they increased rapidly in size and culminated in *Uintatherium*, which had the bulk of a circus elephant and was the largest of the American land animals during late Eocene time.



YALE PEABODY MUSEUM.

Fig. 299. Evolution of the horse, as shown by limbs and skulls from successive zones in the Cenozoic rocks of western United States. The fore limb in each case indicates the approximate height at the shoulder, and the position of the skull shows the height at which the head of each genus of horse was carried.

In short, the Paleocene faunas would have presented a strange, unfamiliar appearance to a modern, for the dominant forms belonged to groups that are long since extinct, and many of the groups that are now dominant were completely lacking.

Eocene Immigrants

At the beginning of Eocene time the ancestors of the modern horse, the rhinoceros, the camel, and other modern groups of mammals appeared simultaneously in Europe and the United States. This sudden advent implies that these modernized stocks had been evolving somewhere in the northern land mass and at this time migrated southward along two different routes. From this stage on, the history of several

of these stocks can be followed in detail and constitutes one of the most fascinating chapters in the history of life.

Cenozoic Parade

Eohippus and His Progeny. The horse was a native of North America from early Eocene to late Pleistocene time and underwent most of its development here. Skeletons assembled from successive horizons reveal a gradual evolution in teeth, limbs, feet, and size hardly equaled for any other stock of animals. The record is graphically shown in Fig. 299.

American Museum of Natural History.

Fig. 300. *Eohippus*, the "dawn horse," from the Eocene (Wind River) beds. This horse was about a foot high at the shoulder. Restoration by Charles R. Knight.

Eohippus,* the "dawn horse," oldest known member of the race, was a graceful little animal, scarcely a foot high, with a slender face, arched back, and long tail (Fig. 300). Its hind feet bore three toes, and the front feet four toes. Its Paleocene ancestor, we may infer, possessed five toes all around, but no such stage has yet been discovered.

The evolution that followed was long and complex but may be epitomized by noting three of the stages intermediate between *Eohippus* and the modern horse, *Equus*.

Of these, *Mesohippus* of the Oligocene, about the size of a sheep (Fig. 299), had three toes on each foot, subequal in size and all touching the ground, so as to share equally in the animal's weight. Its cheek teeth were still low-crowned, as were those of *Eohippus* (Fig. 292).

Merychippus of the Miocene grew to the size of a small pony (Fig. 299). It possessed three toes on each foot, but the middle toe was much the largest, the others failing to touch the ground and dangling like the "dew-claws" of cattle. The jaws of this little horse had

* According to Simpson (1945, p. 136), the name *Hyracotherium* has legal priority over *Eohippus*, having been applied to the same genus in Europe 36 years before the name *Eohippus* was coined. For the present we continue to use the latter name because it is so much more widely known and applied.

lengthened and deepened appreciably, for its molar teeth were becoming high-crowned and prismatic (Fig. 292).

Pliohippus of the Pliocene, the first one-toed horse (Fig. 299), was somewhat larger than *Merychippus,* and had high-crowned teeth (Fig. 292) and long jaws approximating the condition seen in a modern horse. The side toes were represented only by a pair of splint

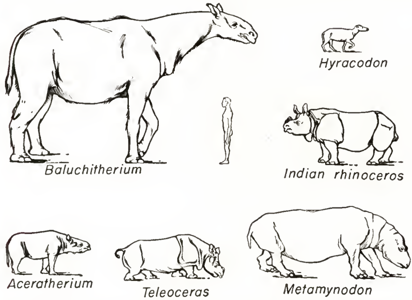


FIG. 301. Fossil rhinoceroses (facing right) and the modern rhinoceros (facing left). The human figure gives the scale. *Hyracodon* is one of the running rhinos of Oligocene date; *Metamynodon* is one of the amphibious rhinos, also of Oligocene date; ***Baluchitherium,*** the greatest land mammal of all time, represents the giant tribe of baluchithere rhinos; the others represent the main line of rhinoceroses.

bones lying alongside of the cannon bone (Fig. 38, p. 64) and invisible externally. The modern horse, *Equus,* appeared about the close of the Pliocene epoch and survived in America until after the last of the Pleistocene ice ages. These wild horses roamed the American plains in great herds until late in the epoch and then, for some unknown reason (possibly an epidemic like the modern hoof-and-mouth disease or sleeping sickness), became extinct. Meanwhile, fortunately, they had spread to the Old World (probably via Alaska and Siberia), where they survived to become a servant and friend of man. The present wild horses are descendants of those brought over by the Spaniards during their early conquests.

Rhinoceroses. The rhinoceros (Fig. 301) also is primarily of North American stock. The group first appeared near the beginning of the Eocene and by early Oligocene time was abundant and had specialized into three distinct tribes: (1) the *true rhinoceroses*, which gradually developed into modern types; (2) the *running rhinoceroses*, which were small, light-bodied, and fleet-footed; and (3) the *amphibious rhinoceroses*, which were semiaquatic and, like the hippopotamus, became thick-bodied and very short-legged. The last two stocks died

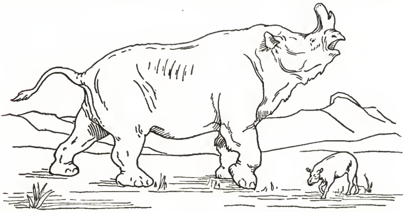


FIG. 302. First and last of the titanotheres. Right, *Eotitanops* of the Eocene epoch; left, *Brontotherium* of the Oligocene epoch. The latter stood about 8 feet high at the shoulders. Adapted from a figure by H. F. Osborn.

out during Oligocene time, but true rhinoceroses were very common in the Great Plains region during Miocene time and were then more varied than they are today in East Africa. One of the striking Miocene forms was *Teleoceras*, a barrel-chested rhinoceros with extremely short legs (Fig. 317). In America the rhinoceroses declined to extinction in the Pliocene epoch, but those which had migrated into the Old World survived.

The early rhinoceroses were small and hornless. The true rhinoceroses were still scarcely 3 feet high in Oligocene time, although one of the amphibious tribe then reached a height of 6 feet and a length of 14 feet. In America few of the Cenozoic forms were as large as modern species, but in Asia an aberrant stock of hornless giants developed during Oligocene and early Miocene time and in *Baluchitherium* (Fig. 301) attained the largest size of any known land mammal of any age. This great beast stood about 18 feet high at the shoulders and was at least 25 feet long.

Titanotheres. Another magnificent tribe of mammals, remotely related to the rhinoceroses and the horses, was the *titanotheres* (Fig. 302). These were ponderous beasts of rhinoceros-like appearance, many of them with great nasal horns made of bony outgrowths from the skull. Early Eocene titanotheres were scarcely larger than a big hog and were hornless, but the tribe developed rapidly to great size before its extinction about the middle of the Oligocene epoch. One of the latest was *Brontotherium,* which stood about 8 feet high at the shoulder and far outbulked the largest living rhinoceros. During Oligocene time this was the largest land animal in America.

Titanotheres are known only from the United States, Mongolia, and Europe. They left no descendants, either collateral or direct. Like the rhinoceros, they possessed three toes on each hind foot and four toes on each front foot. The great weight probably prevented further reduction of the digits in either of these stocks of plains-dwelling mammals.

Chalicotheres. Perhaps the strangest of all the odd-toed mammals were the *chalicotheres,* a group now extinct, but represented by *Moropus* (Fig. 316) in the Great Plains region during Miocene time. The skull of this grotesque creature was shaped like that of a horse, but its body was deep and short-coupled like that of a camel, and its feet bore narrowly compressed claws. There were three toes on the hind feet and three, plus a vestige of the fourth, on the front feet. This is the best-known American form, and its remains are not rare in the Miocene beds of Nebraska; but the chalicotheres were present also in Europe and Asia and are known to have lived from late Eocene to late Pliocene time.

Camels. Camels underwent a long evolution remarkably paralleling that of the horse. One of the earliest genera, *Protylopus* of the upper Eocene, was a slender, four-toed creature scarcely larger than a jack rabbit. By Oligocene time there were camels about the size of sheep associated with *Mesohippus* of the same size. These little camels displayed their true affinities in the enamel pattern of their teeth and in the peculiar carriage of their heads. The toes had by this time been reduced to two on each foot, but these were still free.

In Miocene time the camels diverged into several tribes. The main line continued through *Procamelus* of the Miocene into *Camelops* of the Pliocene and Pleistocene. The latter survived until comparatively recent time in southwestern United States. A larger genus (*Gigantocamelus*) inhabited the Great Plains during Pleistocene time and

reached a height of $7\frac{1}{2}$ feet at the shoulders, carrying its head about 9 feet above the ground.

Among the divergent stocks that appeared in the Miocene were the small and very slender "gazelle camels" and the long-necked "giraffe camels."

Like the horses, the camels lived through the several ice ages in America and then for some unknown reason died out before the arrival of the white man.

Yale Peabody Museum.

FIG. 303. An oreodon, *Merycoidodon gracilis*. Model by Richard S. Lull, based on a skeleton from the Oligocene (White River) beds of Sioux County, Nebraska. The animal was about as tall as a sheep.

Oreodons. One of the most abundant Mid-Cenozoic animals of western United States was the oreodon (Fig. 303). These small creatures are not closely allied to any living animals and are therefore difficult to characterize in nontechnical terms. Most of them were of the size of sheep or goats. Although they appeared long-bodied and short-legged like a hog, this resemblance was quite superficial. In a sense they were remote cousins of the camels, for they had similar teeth, they were even-toed, and they were cud-chewers. They were both browsers and grazers, and, if we may judge by the extraordinary abundance of their remains in the Big Badlands of Dakota, they roamed the plains in vast herds. They appeared in late Eocene time, reached a climax in the Oligocene, and persisted into the early Pliocene before dying out, but during all this time they were strangely conservative, retaining four toes (some a small fifth) and short legs, keeping their low-crowned teeth, and failing to increase notably in

size. Their short-leggedness was a mark of conservatism; their toes had failed to lengthen as rapidly as those of most other plains animals. So far as is known, oreodons were confined to North America.

Entelodonts. The entelodonts, or "giant pigs," were another group of even-toed mammals that assumed a spectacular role for a short time during the Mid-Cenozoic (Figs. 304, 316). They were remote cousins of the swine and, like the latter, were adapted for rooting and grubbing in the forest. They are characterized by a large bony extension from the zygomatic arch of the cheek, a structure whose function is entirely problematic. They appeared during Oligocene time, reached their greatest size (6 feet high at the shoulder) in the early Miocene, and then died out.

Fig. 304. Restoration of an entelodont or "giant pig," *Archæotherium*, from the Oligocene beds of the Great Plains. After W. B. Scott. The largest of the entelodonts stood 6 feet high at the shoulders.

Bovids. Cattle, sheep, and goats belong to the family Bovidæ, which also includes the bison, the musk-ox, and the antelopes. In spite of superficial differences, these animals are closely related and have many peculiarities in common. Among other things, they all lack front teeth in the upper jaw, and they possess true horns with an unbranched bony core covered by a horny sheath. Since the beginning of civilization this great family has contributed more than any other to human welfare. To hunting peoples it has been a source of food and of clothing and tents and thongs as well. Indeed, the very beginning of civilization is closely linked with the domestication of cattle, goats, and sheep, and the tending of flocks.

Unlike the horses and camels and rhinos, this family is essentially an Old World stock. The oldest known forms appeared in Eurasia late in Miocene time, having evolved from stocks now extinct. They became highly diversified there in the Pliocene and reached their modern estate during the Pleistocene epoch, the cattle apparently having developed out of certain antelopes. During the Ice Age most of them migrated out of Europe, finding a more suitable environment in the plains of Asia and Africa, but only a few managed to reach America. The buffalo is one of the exceptions. It probably arrived via the Bering land bridge about the beginning of Pleistocene time, soon became enormously abundant, and developed into numerous

species, some of which were much larger than the living forms. The musk-ox also reached North America in Pleistocene time, having no difficulty in crossing the snowfields of the North.

Elephants and Their Kin. The Indian and African elephants are the sole survivors of a spectacular race that is now verging on

American Museum of Natural History.

Fig. 305. Reconstruction of proboscidian heads, showing stages in the development of tusks and trunk. 1, *Mœritherium* (early Oligocene); 2, *Phiomia* (Oligocene); 3, *Elephas* (Recent). *T*,*T*, incisor teeth; *L*, upper lip; *N*, nostrils. After a drawing by Charles R. Knight.

extinction. During Pliocene and most of Pleistocene time elephants of many sorts ranged over Europe, Asia, Africa, and North America; and, while the last glacial ice was waning, they were still more common in eastern United States than they are now in East Africa.

Compared with the ancestral placental mammal (Fig. 290), the elephants show amazing specialization in several respects. Not the least of these is the fusion of nose and upper lip to form the trunk or *proboscis*, from which this order takes the name *Proboscidia*.

The earliest known proboscidians are found in North Africa, which appears to have been their ancestral home. Several species of the

genus *Mœritherium* (Fig. 305, 1) have been discovered in the late Eocene and early Oligocene beds of the Fayûm Desert not far west of Cairo. When these beds were forming, the climate was humid in North Africa, and the Fayûm area was occupied by the delta of an ancient Nile. The mœritheres were thickset animals scarcely waist-high to a man, and apparently they were semiaquatic, living in and along the river. They had neither tusks nor trunk and showed little resemblance to an elephant; yet they displayed the beginnings of specializations that betray their relationship. As shown in Fig. 305,

Fig. 306. Cheek tooth of mastodon (left) and elephant (right).

1, the head was long and low, and the upper lip was prehensile, as in a modern tapir. Among the front teeth the second incisors were enlarged and bore a band of enamel on the outer side. These are the teeth that developed into tusks in the later proboscidians. The limbs were thick and stout but not otherwise specialized.

In this same region a more advanced type, *Phiomia,* appeared early in the Oligocene epoch, and for a time it lived along with the last of the mœritheres. This animal (Fig. 305, 2) had the proportions of a small elephant and was about shoulder-high to a man. Its jaws were long and its head was low, as compared with an elephant. The second pair of incisors was much enlarged and was directed strongly forward as small tusks, in both the upper and lower jaws. A real trunk was present, though still relatively short. The cheek teeth of *Phiomia* were rather large but low-crowned and bore three pairs of low, blunt cones.

Out of this early stock evolved an amazing variety of animals known as *mastodons.* In most regards they resembled the elephants, but their teeth were quite different (Fig. 306). The name mastodon

(Gr. *mastos,* breast, + *odous,* tooth) refers to the characteristic shape of their cheek teeth, in which the cusps were few in number and occurred as pairs of large blunt cones presenting a fancied resemblance to human breasts.

Phiomia possessed three pairs of such rounded cusps on each molar tooth. Many of its descendants retained this number, but others added one or more pairs of cusps, and in all the later mastodons there was a tendency to unite individuals of each pair by a cross ridge (Fig. 306). The mastodons possessed their normal complement of permanent cheek teeth (six in each side of each jaw) throughout adult life.

Most of the mastodons had tusks in the lower as well as the upper jaw. In many, the lower tusks remained smaller than the upper, but in some stocks they were large and greatly specialized. A striking example is presented by the long-faced *four-tuskers* shown in Fig. 317. In the *shovel-tuskers,* on the other hand, the lower tusks were flattened and broadened to form a scooplike organ, and in the *dinotheres* they were strongly recurved.

Mastodons migrated widely over Eurasia during Miocene time and reached North America near the middle of the epoch via a Siberian-Alaskan land bridge. Among these immigrants were long-faced *four-tuskers* and *shovel-tuskers,* both of which were common in western United States during late Miocene and part of Pliocene time but died out during the latter epoch. More conservative mastodons survived until after the last glaciation, and the fine Pleistocene species, *Mammut americanus* (Fig. 319), may have been exterminated by primitive man within the last several thousand years.

The mastodons were predominantly browsers, living in the timber, and their cheek teeth were relatively unspecialized.

The *elephants,* on the contrary, were grazers and were for the most part at home on the plains. They are readily distinguished from the mastodons by a remarkable specialization of the cheek teeth, in which the cross ridges have become numerous and high and thin. As a result, the tooth is enormous in size, is high-crowned, and is made up of many transverse plates of enfolded enamel embedded in cement (Fig. 306). So large have these teeth become that there is room for only one in each side of each jaw—even in an elephant's mouth! Hence, the full set of teeth does not appear simultaneously, as in the mastodons and other mammals. Instead, one tooth appears in each side of each jaw, and as it is worn out, a second tooth grows down,

crowding out the first and taking its place. In this manner the six teeth that should exist in each half of each jaw succeed one another during the life of the individual, which normally has only four grinding teeth in the mouth at one time. In turn, the jaws have become very short, so that the head of the elephant appears short and high as compared with that of a mastodon (*cf.* Figs. 318, 319).

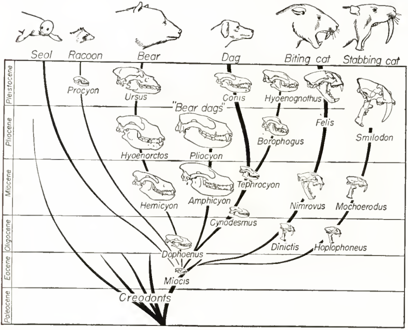


FIG. 307. Family tree of the carnivores, all on the same scale. Note that the "bear dogs," a branch of the canine tribe, attained large size during the Miocene and Pliocene epochs and then became extinct. Diagram based on data from Matthew and Romer.

Of this family (Elephantidæ) the genus *Mammuthus* reached North America during the Pleistocene and was then represented by a number of species. The best known of these is the *woolly mammoth* that lived on the tundra and in the forest bordering the ice fields, and ranged across both Eurasia and northern North America. In Siberia frozen carcasses have been found, showing that it bore a heavy coat of woolly hair (Figs. 13, 318). Other species inhabited the warmer regions, particularly the plains of the central and southwestern states. One of these, the *imperial mammoth* of the Southwest, attained a height of 13 to 14 feet at the shoulders and bore

tusks as much as 13 feet long. In their present fossil state, a pair of such tusks weighs almost half a ton!

Carnivores. Flesh-feeders have a long and complex geologic history (Fig. 307). They are intelligent, travel easily, and are highly adaptive. The dog and cat show their typical specializations—clawed feet, enlarged canines, and narrow shearing cheek teeth. These are devices for holding and devouring active prey. Among the modern forms, the dogs, cats, bears, hyenas, raccoons, and seals represent as many well-defined families, but when they are traced back toward

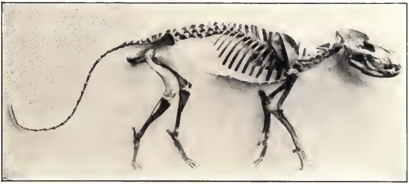


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FIG. 308. Skeleton of a creodont, ***Dromocyon vorax***, from the Eocene (Bridger) of Henry's Fork, Wyoming. Animal about the size of a large dog.

the early Cenozoic, these distinctions decrease, and they seem to converge toward a common Eocene ancestor.

Small primitive carnivores appeared in some abundance in the Paleocene, and during the Eocene epoch they diverged into at least five distinct families, adapted themselves to a wide variety of habits, and attained a considerable range of size, a few reaching the stature of a large bear. Some superficially resembled wolves (Fig. 308) or cats or other living types, but in all these early forms the brains were very small, as compared with those of modern carnivores, and they must have been a stupid lot. Moreover, certain specializations of teeth or other parts show that four of these families were incapable of developing into any of the modern carnivores. For this reason, they are commonly set off as a distinct order, the *Creodonta*.

Nearly all the creodonts were defective or inadaptive in some respects, and three of the families died out by the end of the Eocene, the other barely surviving through the Oligocene, with one genus

ranging up into the Pliocene in India. Thus the first great experiment in carnivore evolution came to an inglorious end!

The fifth family of Paleocene and Eocene flesh-feeders had a higher destiny, even though, at the time, it would have seemed unpromising. It included small slender animals of the size of weasels; but

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FIG. 309. The dire wolf, *Canis dirus*, a common species in the asphalt pits at Rancho La Brea, near Los Angeles, California. Size about that of a modern timber wolf. Pleistocene. Modeled by R. S. Lull.

they had better brains than the rest, and adaptive feet; and their teeth were already specializing in the direction followed by the higher carnivores. Among these small Eocene types, the genus *Miacis* appears as a probable ancestor of all modern carnivores.

This second upsurgence of carnivores was under way in the Eocene, and before the close of that epoch the modern families began to emerge. The dogs were represented by *Pseudocynodictis*, of the size of a fox, and the cats by *Dinictis*, as large as a small leopard.

The Miocene was a time of rapid expansion, and before its close all the modern families were well defined. In the Pliocene formations of western United States several species of wolves are represented, some large and others small, and by Pleistocene time the species were similar to modern ones. In the asphalt deposits at Rancho La Brea in California a common fossil is the dire wolf (Fig. 309), which had the stature of a large gray timber wolf.

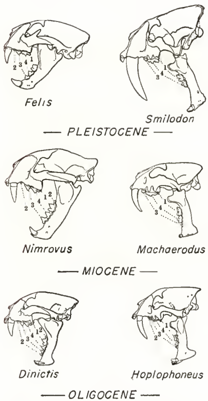

Fig. 310. Skulls of biting cats (left) and stabbing cats (right) arranged in pairs of equivalent geologic date to show parallel development in these two tribes. See also Fig. 307. Adapted from W. D. Matthew.

By Miocene time the cats were diverging into two quite distinct families, the *biting* and the *stabbing* cats. In the former, to which all modern cats belong, the lower and upper canines are subequal, and the lower jaw is strong. Such cats kill their prey by biting. In the stabbing cats the lower canines were small, and the upper ones were extended into saber-like blades; the lower jaw was weak and could be opened to a very wide angle so as to clear the upper teeth, which were then used to stab and tear, bleeding the prey to death (Fig. 310).

The biting cats are well represented in both the Pliocene and Pleistocene deposits of America, culminating in the panther and the lynx. *Felis atrox* of the Pleistocene faunas of southern California was of the size of a lion. The true lion, *Felis leo,* ranged widely over Europe during the interglacial ages of the Pleistocene.

The stabbing cats were even more common from Oligocene to late Pleistocene time, culminating in the *saber-toothed tiger* of the Rancho La Brea tar pits (Figs. 24, 311). It was the last of its race, becoming extinct during the Pleistocene epoch.

Man's Family Tree. Among all the animals, man's closest relatives are obviously the great apes and monkeys; but his family tree also includes two lower branches, the tarsioids and lemurs. All these together constitute the order *Primates* (Fig. 312).

Lemurs (Fig. 313) superficially resemble foxes rather than monkeys. They are distinctly quadrupedal, have long bushy tails, and

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FIG. 311. The great saber-toothed tiger, *Smilodon*, common in the asphalt pits at Rancho La Brea, near Los Angeles, California. Height about 3 feet. Pleistocene. Modeled by R. S. Lull.

run on all fours. Furthermore, their brains are relatively small, their muzzles slender and pointed, and their eyes far apart. Their teeth, however, so closely resemble those of insectivores as to make it quite clear that the primates evolved out of primitive insectivore stock.

The *tarsier* of the East Indies (Fig. 314) is the sole survivor of a group of small primates that was far more common and more widely distributed during the early part of the Cenozoic era. In nocturnal habits and some other respects the living form is highly specialized, but its ancestors among the fossil tarsioids bridge the gap between lemurs and monkeys. When compared with the lemurs, for example, tarsioids have a relatively larger brain and a shorter muzzle, but the most significant advance is in the eyes, which have migrated to the

front and are so close together that both can focus on the same point. This permits stereoscopic vision, an achievement which no other animals have attained save the monkeys and apes and man.

From the start, the primates specialized for an arboreal life, finding in the trees a refuge from their more powerful enemies on the ground. Prehensile hands and feet, with opposable thumb and great toe, were developed early; and the depth of focus inherent in stereoscopic vision opened new possibilities for locomotion in the trees. Instead of running along the limbs like a squirrel, such animals could safely hang by their arms and swing from limb to limb or even from tree to tree. Such free and rapid locomotion through the forest had great selective value. It led first to the evolution of the monkeys and shortly thereafter to gibbon-like apes, in which the arms are longer and more powerful than the legs. This in turn opened up new possibilities when the forests shrank, during late Cenozoic time, and some adventurous apes returned to life on the ground, for now their long arms gave them almost an upright position even when walking on all fours. Bipedal gait was thus easy to achieve and the hands were freed for better uses. Special interest therefore attaches to the tarsioids, whose vision in Paleocene time started us on the highway toward the human estate!

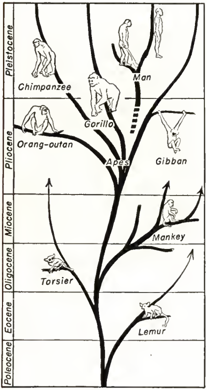

FIG. 312. Man's family tree.

The lemurs and tarsioids were well adapted to the mild, moist climate that prevailed over Europe and the United States during the early part of the Cenozoic era, and their fossil remains are relatively abundant, though fragmentary, in both these regions in Paleocene and Eocene strata. But during Oligocene time subtropical forests gave way to open plains in the present temperate lowlands, and the

primates retreated to lower latitudes. During the Miocene and Pliocene epochs the climate generally became both cooler and drier, and the tropical and subtropical forests gradually shrank to their present distribution. As a result, most of the higher primate evolution took place in parts of Africa and Eurasia that are not yet well known paleontologically.

Lemurs and tarsioids died out in the United States during Oligocene time, and no record whatever is known of monkeys or apes in all of North America. Small monkeys had reached South America (or had evolved there out of tarsioids) and survive to the present, undergoing an evolution entirely independent of the rest of the world, and reaching no greater attainment than that of the cebid monkeys used by itinerant organ-grinders.

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FIG. 313. Galago, the bush baby, a small lemur of rather advanced type from northern Rhodesia, Africa. The body of the animal is about 6 inches long.

The earliest evidence of Old World *monkeys* is a lower jaw with most of its teeth, found in Lower Oligocene beds of Egypt. The Miocene record is still very meager, and that of the Pliocene only somewhat better. Tropical forests provide a very poor environment for the preservation of fossils because the organic acids in the soil cause rapid decay of bones. For this reason we may never have as much evidence for the geologic history of the primates as for most of the other groups of animals. Pliocene monkeys are referred to families still living.

The manlike *apes* (Fig. 315) include four living types—the gibbon, the orang-outan, the chimpanzee, and the gorilla—and a number of fossil genera. In these the arms are longer than the hind legs, so that when walking on all fours the body is in an almost upright position, and bipedal gait is not difficult.

Although the living great apes are more manlike than any other animals, each type is highly specialized for a lazy life in the tropical forest, and none could possibly be considered the direct ancestor of man. Instead we must go back to fossil forms of the Pliocene or

older for the stock that left the forest and returned to the ground. The oldest evidence of a manlike ape yet known is an incomplete lower jaw with two premolars and one molar tooth. It was found in the Eocene beds of Burma and has been named *Amphipithecus*.[2] The next oldest record is a jaw of *Propliopithecus* found in the Lower Oligocene beds of Egypt, along with that of the first monkey. A third genus, *Dryopithecus*, known from numerous jaws and other fragments found in Miocene beds of both Africa and Europe, is believed to be near the common line that led to the living great apes and man. Pleistocene cave deposits of South Africa have yielded the most complete remains of fossil apes, including a well-preserved skull with most of the face. These remains represent an ape, *Australopithecus*, with a brain rather larger than that of any modern type. Pleistocene beds of both Java and southern China have yielded very fragmentary remains, chiefly teeth, which indicate primates of giant size, at least twice as big as the living gorilla.

Lilo Hess photo.

FIG. 314. Tarsier, a native of the Philippine Islands, now in the New York Zoological Gardens. About natural size.

The human stock was the last of the primates to appear. The known geologic record of man begins with the Pleistocene epoch and is the special subject of Chapter 20.

RECAPITULATION

Paleocene Faunas. "The most dramatic and in many respects the most puzzling event in the history of life on the earth," G. G. Simpson has said, ". . . is the change from the Mesozoic, Age of Reptiles, to the . . . Age of Mammals. It is as if the curtain were rung down suddenly on a stage where all the leading roles were taken by reptiles, especially dinosaurs, in great numbers and bewildering variety, and rose again immediately to reveal the same setting but an entirely new cast, a cast in which the dinosaurs do not appear at all, other reptiles are mere supernumeraries, and the leading parts are all played by mammals of sorts barely hinted at in the preceding acts."

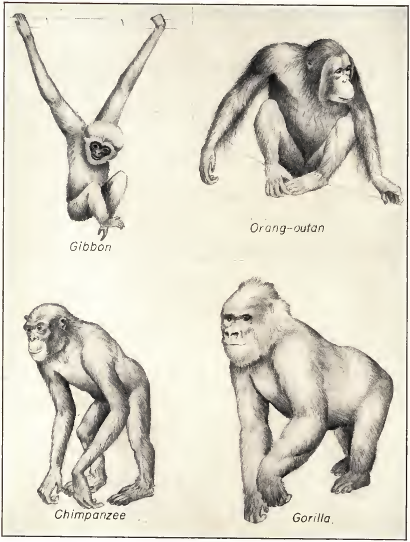

FIG. 315. Manlike apes. The four living types of manlike apes are shown here at the same scale. The gibbon and the orang-outan inhabit southeastern Asia and the Netherlands East Indies; the chimpanzee and the gorilla inhabit the tropical forests of Africa.

Clearly these Paleocene mammals came for the most part as migrants from some region (probably northern Asia) where they had been developing even before the close of the Mesozoic. Among them were holdovers of three groups already known in the Cretaceous world —multituberculates, marsupials, and insectivores. But the dominant groups—condylarths, amblypods, and creodonts—belonged to three "archaic" orders that appeared suddenly, thrived for a while, and then died out. Although these orders lived on into Eocene time and some then attained considerable size, the Paleocene species were small, the largest scarcely exceeding the size of a hog or a small bear.

With these "archaic" stocks were associated the forerunners of several orders that are still extant, notably the rodents and primates, but these were all small.

Nearly all the Paleocene mammals had long narrow heads with small braincases and long slender muzzles. They were quadrupedal, with fore and hind legs nearly equal in length. All had five toes, and the earliest known examples of each stock walked on the sole of the foot. The distinction between the marsupials and all the rest was already so complete as to suggest that the placental mammals were not direct descendants of the marsupials, but cousins descended from a common Mesozoic ancestor.

Eocene Faunas. The most striking feature of the early Eocene life was the appearance in considerable numbers of progressive forms ancestral to the modern orders of mammals. Among these were diminutive *horses,* small hornless *rhinoceroses,* equally small *titanotheres,* tiny *cameloids,* the first *oreodons,* squirrel-like *rodents, bats,* and small *primates.* None of these attained a considerable size, and the largest would hardly have stood waist-high to a man.

With them were associated the "archaic" mammals, some of which were far larger. *Creodonts* were the carnivores of that time, and of these some were doglike, some hyenalike, and others more catlike. Common American types reached a maximum size only about that of a modern timber wolf, though one of the latest Eocene types was as large as a great bear. The greatest of all Eocene carnivores, however, was the Mongolian *Andrewsarchus,* with a skull about 2½ feet long. The *condylarths* were common during the early half of the epoch but died out before its close. The great animals of this time were the ponderous *amblypods,* which increased gradually to their maximum bulk in *Uintatherium* of the late Eocene.

In the later Eocene occurred the first mammal adaptation to a marine life, in the form of whalelike animals (zeuglodons), whose

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Fig. 316. Early Miocene landscape in Nebraska, showing "giant pigs" in center foreground, Moropus browsing on tree at right, and three-toed horses in middle distance at extreme left. From a painting by Charles R. Knight.

fossil bones occur abundantly in parts of our southern states, in Egypt, and in Europe. One of these, *Basilosaurus,* must have been the "sea serpent" of its time, with 4 feet of head, 10 feet of body, and 40 feet of tail! But even a mammal of this size met its match in the great sharks of those seas, the gaping jaws of one of which (*Carcharodon*) must have been about 6 feet across.

Oligocene Faunas. By Oligocene time, the modernized types comprised nearly the entire mammalian fauna. A single genus of creodonts remained, but amblypods and condylarths were wholly extinct, and marsupials and insectivores were as inconspicuous as they are today. In western America the *oreodons* roamed in vast herds over the plains. Three-toed horses (*Mesohippus*) scarcely larger than sheep were common. *Rhinoceroses* of several kinds were present, the largest of them being amphibious, though not related to the hippopotamus. Probably all the Oligocene species were hornless. The *titanotheres* displayed a meteoric evolution, and with the exception of the giant Asiatic rhinoceros, *Baluchitherium,* they became the largest land animals of this time before dying out abruptly about the middle of the epoch. Small camels were present, and so were peccaries and tapirs. The rodents were represented by beavers, squirrels, rab-

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Fig. 317. Late Miocene landscape in Nebraska, showing at the left a group of short-legged rhinoceroses, and at the right a pair of four-tusked, long-jawed mastodons. From a painting by Charles R. Knight.

bits, and mice. Among the carnivores there were many small *dogs*, as well as both *biting* and *stabbing cats*. In the Old World the Proboscidea were beginning their career, being represented by the first mastodons, which were only about 5½ feet high. Early primates had become extinct in North America, and the only known great ape was represented in Europe by a single species.

Miocene Faunas. The Miocene was the "Golden Age" of mammals (Figs. 316, 317). The spread of the prairies and the change to more arid climate led to rapid evolution of the grazing stocks, and the formation of a Bering land bridge permitted intermigration between North America and Eurasia.

Within the groups of animals already present there was a rapid expansion into new genera and species and an increase in size in many stocks. The habit of feeding on the harsh prairie grasses resulted in a remarkable change in the teeth of many groups, whereby the jaw teeth became long and prismatic and continued to grow throughout life, thus counteracting the rapid wear at the crowns. *Horses* now attained the size of small ponies, but the many species all had dangling side toes. *Camels* were especially abundant and varied, some being little larger than sheep, while others rivaled the modern giraffe in height. *Oreodons* were still very common. *Rhinoceroses* of several kinds were abundant. At this time the "giant pigs" reached their climax in a species (*Dinohyus hollandi*) known from Nebraska that was as tall as an ox and had a skull 4 feet long. *Moropus*, the

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Fig. 318. Pleistocene landscape in Europe during the last Ice Age, with woolly mammoth in the foreground and woolly rhinoceros in the right middle distance.

clawed ungulate, was also most common at this time. *Rodents* like those of the Oligocene continued through the Miocene. Of *carnivores* there were numerous wolflike dogs, as well as biting and stabbing cats. There were no North American primates, but in the Old World a great ape (*Dryopithecus*), somewhat related to the gorilla, but much smaller, ranged over Europe and northern Africa. The four-tusked proboscidians arrived in America.

Pliocene Faunas. The Pliocene faunas of North America are still imperfectly known because the terrestrial formations of this age are so sparsely preserved. At this time there was further immigration from the Old World, bringing us the *true mastodons*. *Horses* continued their rapid evolution and were represented in America by several genera, among which appeared the first single-toed horse, *Pliohippus*. *Rhinoceroses* were still very abundant. *Camels* continued to be among the most common animals of the plains. The last straggling survivors of the oreodons were extinct before the close of the epoch.

Pleistocene Faunas. Throughout the Pleistocene epoch North America and Europe were both inhabited by great game animals fully as varied and impressive as those of modern East Africa. In the United States the *elephants* were perhaps the most impressive, for there were at least 4 species, 2 of which exceeded modern elephants in size. The tall, rangy imperial mammoth of the southern Great Plains stood nearly 14 feet high at the shoulders. Another species (*Mammuthus arizonæ*) was at home in the basins of Arizona and

Fig. 319. Scene in the Mississippi Valley during Pleistocene time. At the left, the American masto-

Nevada. Numerous remains of *Mammuthus columbi* and *M. imperator* have been found in the uppermost beds of glacial Lake Bonneville, and these elephants must have been common in the Great Basin region until after the last of the glacial ages. Throughout the forests mastodons (*Mammut americanus*) browsed in great herds (Fig. 319); their remains are common in the peat bogs of the eastern states, no fewer than 217 individuals having been discovered in the bogs of New York State alone. In Florida, New York, and elsewhere the remains of this species are associated with human artifacts in such a way as to indicate that mastodons survived the last ice age and may have lived until within the last several thousand years. The woolly mammoths (Fig. 318) ranged widely over the glaciated areas, extending northward into Alaska and eastward across Siberia, where their skeletons and tusks are still incredibly numerous in the frozen soil, about half the present ivory of commerce being derived from this source. Siberian ivory was imported into China as early as the fourth century B.C., and began to be extensively transported into Europe early in the nineteenth century. Between 1800 and 1850 the annual sale of tusks at the trading center of Yakutsk averaged about 18 tons, and to date not less than 46,750 pairs of tusks have been recovered in Siberia.[3]

Horses were still common, and at least 10 species are known from North America. Most of these were of the size of small ponies, but one fully equaled the greatest modern draught horse. *Buffaloes* roamed the plains in great herds as they did when the white man first reached America. There were at least 7 Pleistocene species, and one of these (*Bison latifrons*) was a colossal beast with a horn-spread of fully 6 feet (Fig. 319). *Camels* also were common. *Wild pigs* (pec-

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don; center, the Royal bison; right, the wild horse, Equus scotti. From a mural by Charles R. Knight.

caries), now confined to Texas, Mexico, and Central America, then ranged over the United States.

Carnivores were abundant and varied, including species of such modern types as the wolves, foxes, pumas, lynxes, raccoons, badgers, otters, skunks, and weasels. In addition, there were extinct types of which the great saber-tooth (*Smilodon*) was perhaps the most striking. Another great cat (*Felis atrox*), also known from the tar pits of Rancho La Brea, was very much like the modern lion in form and size. The great wolf (*Canis dirus*) which was so common in southern California exceeded in size any modern American canines. True bears apparently made their appearance in America at this time as immigrants from the Old World.

One of the most striking elements of the Pleistocene fauna was due to the immigration from South America of the *glyptodonts* and the great *ground-sloths*. These both reached Texas in the Pliocene, and the latter spread over the United States in the Pleistocene. The ground-sloths (Fig. 24, p. 43) were clumsy beasts with the bulk of an elephant, but they were short-legged and curiously club-footed—their ancestors had lived so long in the trees and had developed such long, curved claws that it was impossible for them to walk on the bottoms of the feet when they became too heavy to live longer off the ground. These creatures are common fossils in the tar pits of southern California, and at least one genus (*Megalonyx*) ranged eastward to the Atlantic States. A claw of this form was discovered in a cave in Virginia by President Jefferson, who was the first to describe and name the genus but thought it to be a mighty lion.

North and South America were separated throughout Cenozoic time until they became united by the present Isthmus of Panama in the

late Pliocene. Just before this connection, South America had 29 families of mammals and North America 27, but with 2 doubtful exceptions they had no families in common. Shortly afterward, in the Pleistocene, they had 22 families in common, 7 of South American origin and 14 of North American origin and 1 doubtful. Those emigrating to South America included the mastodons, horses, tapirs, camels, and peccaries; those coming in the opposite direction included the ground-sloths, armadillos, and glyptodonts.[4]

Another striking element of the Pleistocene faunas was supplied by the arctic animals that migrated southward during the glacial ages. For example, the musk-ox is recorded as far south as Arkansas and Utah, while in Europe the reindeer, the woolly rhinoceros, the woolly mammoth, and the arctic fox ranged southward into France and Poland.

There were no primates in North America until primitive man reached here from the Old World. Although evidence of the presence of early man in America has been claimed repeatedly, it is still scanty. On the other hand, savage races were present in Europe and in eastern Asia and northern Africa throughout much if not all of the Pleistocene epoch. The geologic history of man is reserved, however, for a special chapter.

In Europe, the Pleistocene fauna of the warm interglacial ages included most of the types of great game animals now found in Africa. Such, for example, were the lion, the rhinoceros, the hippopotamus, the elephants, antelopes, and lesser animals.

Contemporary Life

Spread of the Prairies. Forests were essentially modern at the beginning of the Age of Mammals. Most of the genera of hardwood trees had appeared during the Cretaceous period, and their subsequent evolution has been in the main a matter of specific details. On the contrary, the development of the grasses during this era was one of the great milestones in the history of life, and for the evolving mammals its importance can hardly be overemphasized. It is this stock, for example, that includes not only the forage plants but also the cereals—notably wheat and rice and oats and corn—that provide the basic food supply for the modern world.

Grass is poorly adapted for preservation, and almost no direct evidence of its early history is known. However, it contains an

appreciable amount of silica and tends to wear out the grinding teeth of the grazers, that is, grass-feeders. To compensate for such wear, the modern plains mammals have high-crowned cheek teeth that grow at the roots throughout life (Fig. 292). Pre-Miocene representatives of each of these groups, like the modern forest-dwellers that browse on more succulent leaves, had low-crowned cheek teeth. It appears evident that the high-crowned grinding teeth are a direct adaptation to a grazing habit; and since this specialization began early in the

M. K. Elias.

FIG. 320. Seeds of grasses and other herbs. Left, the spear grass, *Stipidium commune*, from the Pliocene (Valentine formation) near Wray, Colorado; right, the borage herb, *Biorbia fossilia*, from the Pliocene (Ash Hollow formation) near Castle Rock, Kansas.

Miocene, it is inferred that prairie grass had then, for the first time, become widespread. About 1940, fossil grass seeds were discovered in some of the sandy beds of western Nebraska,[5] and it was soon found that they are abundant over the High Plains region in beds ranging from Mid-Miocene to late Pliocene date (Fig. 320). Careful search in the underlying early Miocene and Oligocene deposits of the same region has thus far been in vain.

Other herbaceous plants are still imperfectly known, but roses with characteristic leaves and thorns have been found in the Oligocene, and unmistakable leaves and seeds of the grape occur in Eocene and later rocks of both Europe and America. Petrified grape vine is known from the Miocene beds of Nevada.

Modernization of the Invertebrates. The invertebrate animals, like the forest plants, had practically accomplished their present evolution before Cenozoic time. A few of the modern species were al-

ready living in the Eocene epoch, and many were extant in the Miocene.

Special note should be made, however, of the *nummulites,* a family of very large Foraminifera having discus-shaped, or coin-shaped, multichambered shells (Fig. 321). They were extraordinarily abundant in the seas of the Mediterranean region during Eocene and Oligocene time, and their shells contributed largely to the *nummulite limestones* that are widely distributed in southern Europe, northern Africa, and the Himalayan region, where the Eocene is still commonly spoken of as the "nummulitic period." Such shells are less common in the American Eocene but do appear abundantly in the upper Eocene and Oligocene of Florida and the Caribbean region.

Yale Peabody Museum.

Fig. 321. A chunk of nummulitic limestone from one of the pyramids of Egypt. Herodotus (about 450 B.C.) alluded to this stone as an instance of petrified animals. Natural size.

Decline of the Reptiles. With the extinctions at the close of the Mesozoic, the reptile dynasty collapsed. Turtles, crocodiles, and lizards lived on about as they are today, except that large land turtles and alligators were more widely distributed during the warmer times. Fossil turtles are abundant in the badlands of Oligocene and Miocene age. Enormous species, large enough to stand waist-high to a man, were common in Florida in Pleistocene time. As noted before, alligators occur frequently in the Eocene and Oligocene deposits

as far north as Wyoming and the Dakotas. Snakes are first recorded in the Late Cretaceous and therefore existed throughout the Cenozoic, but, because of their retiring habits and their delicate skeletons, they are always rare fossils. An Eocene species related to the modern boa constrictor and estimated to be 35 feet long was found recently in Patagonia.

Birds. Modern types of birds, all toothless, appeared in the Eocene, and even at that early date most of the present orders were represented. Such, for example, were the eagles, vultures, pelicans, quail, and various shore birds. All these stocks persisted through the Cenozoic, though fossil remains are, in general, rare because the bird skeleton is fragile.

FIG. 322. *Phororhacos*, a giant flightless bird of the Miocene of Patagonia. Drawn by Charles R. Knight. From Lucas, *Animals of the Past*.

Nearly all the continents at one time or another during the Cenozoic had large, flightless birds. One of these (*Diatryma*), known from the early Eocene beds of Wyoming, stood nearly 7 feet high and had a very stout neck and a head almost as large as that of a horse. Another (*Phororhacos*), found in the Miocene of the Argentinian pampas, stood 7 to 8 feet high and had a very massive skull 23 inches long with a strongly hooked beak (Fig. 322). It was undoubtedly the greatest of all birds of prey. The largest bird, however, was an ostrich-like form, *Dinornis*, that lived into historic time in New Zealand and was exterminated by the Maoris only a few centuries ago. This enormous bird stood about 10 feet high and was therefore more than 2 feet taller than the greatest living ostrich. Still another giant (*Aepyornis*) of Madagascar laid the largest known eggs, which normally measured 13 inches long and 9 inches across. Discovery of the eggs of this bird by early navigators inspired the thrilling tales of the roc told by Sindbad the Sailor in the *Arabian Nights*.

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Chapter 20

THE COMING OF MAN

Prehistoric Documents

Artifacts. The American pioneers found the Indians using stone implements instead of metal. Flint provided tips for their arrows and blades for their tomahawks, and stone mortars served as mills for the grinding of maize. To these early settlers there was no mystery attached to the finding of such carefully shaped stones where the Indians had once pitched their camps.

Similar stone implements found in western Europe, however, were regarded with strange superstition throughout the Middle Ages, and were commonly thought to be thunderbolts. The civilized world at that time had little contact with primitive peoples, and, moreover, it was completely dominated by the belief in a Special Creation that left no place for extinct races of men antedating the present civilization. Yet stone implements are abundant in parts of Europe and were commonly collected as curios after the Renaissance, and we find Olaf Worm, a Danish authority on such objects, writing in 1655 that "they are commonly supposed to fall with the lightning from the sky," though "opinions differ as to their origin, since some believe they are not thunderstones but petrified iron implements, seeing they resemble the latter in shape so closely." And as late as 1802, Thorlacius, writing of stone artifacts discovered in burial mounds, concluded that "the objects found in the mounds are nothing else than symbols of the weapons employed by the Gods of Thunder in chasing and destroying evil spirits and dangerous giants. They could not be ordinary tools and weapons as these have been made of metal since the earliest times."

It now seems strange that a belief so fantastic could have persisted for 300 years after Europeans had encountered the American Indians using stone implements; it sprang from the assumption that such savages were pre-Noachian degenerates who had wandered far from the original center of civilization and had lost the art of working

metal. Occasional thinkers, far ahead of their time, had, indeed, realized the true meaning of archeological remains since before the beginning of the Christian era, but it was not until within the last century that these remains were generally accepted as evidence of prehistoric races. Even then, no one considered the possibility that they might represent the work of extinct *species* of man until after Darwin's *Origin of Species* had paved the way for a belief in the gradual evolution of man from the lower animals.

The appreciation of the true meaning of stone artifacts was first developed in Scandinavia shortly after 1830. It began with the creation by the Danish Government of a scientific commission to study the refuse heaps and shell mounds that had already attracted attention in the region. As a result of this project, extensive collections were assembled at the Royal Museum in Copenhagen and were studied with respect to their stratigraphic occurrence in the mounds. On this basis, Thomsen, the director of the Museum, in 1837 proposed a chronology of human culture divided into the *Stone Age,* the *Bronze Age,* and the *Iron Age.*

Man undoubtedly advanced through this sequence of cultures on the way to civilization, but in western Europe the making of bronze and the smelting of iron had been mastered while aborigines in many parts of the world were still using crude stone implements. Thus the Iron Age in Europe was contemporaneous with the Stone Age in many other parts of the world. Thomsen's chronology is therefore only applicable locally.

The tools and other implements used by a people represent its *culture.* The style of workmanship changed with time during the Stone Age, just as it does in the modern world; and as it is easy to distinguish the relative ages of a collection of colonial flintlocks and one of modern high-power rifles, so it is also possible to distinguish different cultures of stone implements. Accordingly, other workers, following Thomsen, further subdivided the Stone Age into three stages, Eolithic, Paleolithic, and Neolithic, based on the type of workmanship displayed. Of course, these subdivisions also have only local value as time units.

The first tools used by man were doubtless those accidentally shaped by nature to fit his hand, such as sharp-edged chips of flint that he could use to scrape skins or to fashion wooden tools. Such stones, which he picked up and used without modification, are known as *eoliths* (Gr. *eos,* dawn, + *lithos,* stone). Showing evidence of wear but not of conscious shaping, they represent the lowest stage of human

Fig. 323. Stone implements. Number 1 is an eolith, 2–7 are paleoliths, and 8 is a neolith. Number 1 represents a pre-Chellean culture; 2, a Chellean culture; 3 and 4, Mousterian cultures; 5 and 7, Solutrean cultures; 6, Aurignacian culture; 8, a Neolithic culture from Denmark.

culture and are found in formations as old as the late Pliocene (Fig. 323).

Eventually man learned to flake off pieces of stone and to shape them, by chipping, into scrapers, hand axes, spear heads, and other useful tools. This was an art slowly acquired through countless generations of trial and experiment by primitive peoples whose lives often depended on the quality of their weapons. Such artifacts, shaped by chipping alone (Fig. 323), are known as *paleoliths* (Gr. *palaios,* ancient, + *lithos,* stone), and cultures represented by such implements characterized the *Paleolithic* age, which endured in Eurasia until a few thousand years ago.

In Europe some of the prehistoric peoples advanced a stage farther in the making of stone implements which they shaped and sharpened by grinding and polishing against natural abrasive stones. Such objects, known as *neoliths* (Gr. *neos,* recent, + *lithos,* stone), are found only in deposits younger than the last glacial till in northern Europe, and they mark the highest Stone-Age culture, attained in Europe shortly before the discovery of the use of copper.

Metals first began to replace stone for implements about 5000 B.C., copper and bronze (an alloy of copper) being employed sooner than iron because they are easier to smelt. The art of working copper began apparently in Egypt and had spread to Chaldea as early as 4500 B.C., but it was unknown in Europe until about 1500 B.C. Iron implements were developed by the Egyptians as early as 3000 B.C. and iron swords were in use in Greece between 1400 and 1300 B.C., but the iron industry did not spread to central Europe until about 800 B.C.

The succession of cultures in Europe is shown in the table of human prehistory on p. 504.

Human Fossils. Prehistoric human remains are, for obvious reasons, among the rarest of fossils. With his superior intelligence, man generally avoided such common catastrophes as miring and drowning. Of course this did not reduce the number who died, but it lessened the chances for burial where preservation would be likely. Furthermore, funeral rites, observed by man since very remote times, commonly resulted in destruction of the remains, whether the funerals involved cremation, elevation on scaffolds, or burial in shallow graves, since the graves were generally placed on elevated mounds where both weathering and erosion are active.

A fortunate exception was provided by the cave dwellers, who took refuge in caverns or overhanging shelters along the river bluffs of

G. G. MACCURDY.

Fig. 324. Rock shelter of Les Eyzies, Dordogne, France. The re-entrant along the middle of the cliff was occupied by Paleolithic man.

Europe and parts of Asia during the late Pleistocene, finding there a shelter from the inclement weather and a refuge from the powerful carnivores of the time (Fig. 324). These peoples commonly buried their dead in the caverns where they also would be safe from the ravages of wild beasts—and, fortunately for us, they surrounded them with food and weapons intended for use in the future life. Such cave burials therefore give us not only the physical characters but also the culture which was actually used by the individual preserved. Thus we find a tie-up between the human fossils, which are rare, and the definite cultures of stone implements, which are widely scattered and almost indestructible. Such burials also commonly include two or more individuals, thus giving us a record of both sexes and of the young as well as the old.

Until it was admitted that extinct races had preceded the present inhabitants of Europe, human fossils were not recognized as such and, if observed, were considered merely the remains of buried dead. But in 1857 there was found in the Neander Valley near Düsseldorf, Germany, a type of skull obviously unlike modern man in many charac-

teristics. After the publication of Darwin's *Origin of Species* in 1859, this skull was soon seen to be the record of an extinct species far more apelike than any living men, and it became the type of the Neandertal race. During recent years, the present interest in human antiquity has led to increasingly numerous discoveries, until approximately 100 localities have now yielded human fossils. The majority of these are associated with caves and rock shelters, but several are in river terraces or lake deposits and record accidental deaths and natural burial.

Dating the Record. Paleolithic man was a hunter, procuring both food and clothing from the game he could kill. His weapons were adapted to this end, and his camp sites were surrounded with the bones of his prey. As he lived through the last ice age in Europe, his environment changed greatly with the advance and retreat of the glaciers. In addition to the climatic differences between glacial and interglacial ages, he experienced great changes in his food supply. During the last glaciation, for example, an arctic fauna ranged southward to the Mediterranean, including the arctic fox, the woolly mam-

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Fig. 325. Cave of the Kids in the Valley of the Caves (Wady el Mughara) in Palestine. Before this group of caves there is stratified refuse about 70 feet thick, a succession of eleven prehistoric cultures ranging from the pre-Acheulian to the Bronze Age.

moth, and vast herds of reindeer. The last named became at that time the chief source of human food and clothing. But during the preceding interglacial age the reindeer had been restricted to the Arctic, and temperate and subtropical game had spread northward over Europe, including, among other creatures, the lion, the hippopotamus, the elephant, and great herds of wild horses. At that time the horse was the chief object of the chase.

Thus, throughout the million years or so represented by the Stone Age in Europe, the steady evolution of the mammalian faunas was

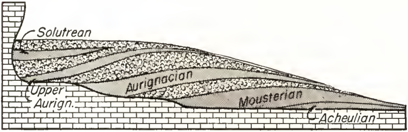


Fig. 326. Diagrammatic section of the stratified deposits before the rock shelter of Laussel, France, showing a succession of five distinct cultures. The layers bearing artifacts are stippled, and the cultures are named. Adapted from G. G. MacCurdy, *Human Origins* (D. Appleton and Company).

accentuated by extensive north and south migrations induced by the glaciation. Accordingly, the different stages of the Pleistocene, represented south of the limits of glaciation by outwash and terrace gravels, contain quite distinctive mammalian faunas. The succession of faunas, worked out from many occurrences, provides the key for dating the human records.

Fortunately for us, primitive man had little notion of sanitation, and camp refuse was thrown away to accumulate over the slope below many shelters that were long inhabited. Of course this refuse included broken or discarded artifacts as well as bones. The most-favored camp sites were used in succession by different peoples throughout much of Paleolithic time, and the refuse of each in turn accumulated to form a roughly stratified deposit. One of the thickest and most complete records known is that about the Cave of the Kids in the Valley of the Caves in Palestine (Fig. 325), where stratified refuse about 70 feet thick includes distinct layers representing eleven different cultures, ranging from early Paleolithic time to the Bronze Age (*cf.* Fig. 326).

In dating actual human fossils, it is always necessary to make sure that the bones have not been artificially buried in layers of sediment of much older date.

A CALENDAR OF HUMAN HISTORY

(From *Glacial Geology and the Pleistocene Epoch,* R. F. Flint)

Geologic Time Units			Dates in Years, B.C. (*estimated*)	Cultural Stages			Types of Fossil Man	
	North America	*Europe*						
Pleistocene epoch	Wisconsin glacial age	Fourth glacial age	5,000	Age of Metals			*Homo sapiens*	Modern man
			6,500	Neolithic				
				Mesolithic				
			15,000	Paleolithic	Late	Azilian		*Cro-Magnon man*
						Magdalenian		
			55,000			Solutrean		
						Aurignacian		
			100,000					
	Sangamon interglacial age	*Third interglacial age*	225,000		Middle	Mousterian	*Neandertal man*	
	Illinoian glacial age	Third glacial age	325,000		Early	Acheulian Levalloisian		
	Yarmouth interglacial age	*Second interglacial age*	600,000			Chellean	*Heidelberg man*	
						Choukoutienian	*Peking man*	
	Kansan glacial age	Second glacial age	700,000			Clactonian	*Pithecanthropus*	
							Swanscombe man	
	Aftonian interglacial age	*First interglacial age*	900,000			Pre-Chellean	*Piltdown man*	
	Nebraskan glacial age	First glacial age	1,000,000+					
Pliocene epoch				Eolithic				

MEN OF THE OLD STONE AGE

Flint Workers of England. The most ancient relics of mankind are found in England. Near the city of Ipswich, about 65 miles

northeast of London, the upper Pliocene beds include seven layers that have yielded abundant eoliths, now accepted by archeologists as the implements of primitive man. About 60 years ago there was also found here a stiletto made of a deer horn. The locality has particular interest because the flint implements lie under a fossiliferous marine bed that proves conclusively the Pliocene age of the deposit.

Slightly younger deposits (early Pleistocene) of similar nature are found at Foxhall, a few miles northeast of Ipswich, and there the flints are associated with charred wood, suggesting that the ancient flint workers had already discovered the use of fire. At Cromer, still farther northeast of London, there is another bed (the Cromer Forest bed) of early Pleistocene age, from which large but crudely chipped flint implements have been recovered. In none of these localities have any skeletal remains been found, but the crude implements indicate clearly the presence of man in England at the close of the Pliocene and early in Pleistocene time.

Pithecanthropus. The most discussed of all human fossils was discovered in 1891 by Eugene Dubois, a Dutch army surgeon stationed on the island of Java. He had opened a quarry for vertebrate fossils in a 3-foot bed of gravel exposed in the bank of Solo River, and there he came upon several human bones—a skull cap, a left thigh bone, fragments of nasal bones, and three teeth. Although each bone was isolated, and the thigh bone was found almost 50 feet from the skull, Dubois assumed that they belonged to one species if not to one individual.

The skull cap was remarkably thick, the brow ridges very massive, and the forehead low and receding. The brain of this skull, estimated to have had a volume of 900 cubic centimeters, is intermediate in size between that of the largest apes (about 600 cubic centimeters) and the average for the lowest types of living men (about 1240 cubic centimeters). Moreover, the scars of attachment for the great neck muscles at the base of the skull clearly imply that the head was carried forward, as in the apes, instead of being well balanced on the neck, as in modern man.

Soon after discovery, this find was hailed as a "missing link" between the apes and man and was given the name *Pithecanthropus* (Gr. *pithecos,* an ape, + *anthropos,* a man). Almost at once it became a subject of controversy. Skeptics argued that this was an abnormal individual, perhaps an idiot; but statisticians pointed out the extreme improbability of an abnormal individual being the sole one to be

preserved and discovered. All uncertainty was cleared up by the extensive and careful restudy of the area by Weidenreich between the years 1935 and 1940, which brought to light three additional skulls. The last and most important of these (Fig. 327) includes the upper

FIG. 327. *Pithecanthropus erectus.* Skull No. IV, found by Von Koenigswald in 1939, as restored by Franz Weidenreich. The darker parts are actual bone; the lighter parts are restored by comparison with other skulls of the same species.

jaw, part of the lower jaw, and several teeth, along with the posterior and basal part of the braincase. It is somewhat larger and more massive than the original skull and is believed to be that of a male, whereas the original was female. These skulls fully confirm the interpretation previously made of the brain size and the shape of the head and face of *Pithecanthropus,* and prove beyond possible doubt that this is a well-defined but primitive human type. On the other hand,

the thigh bone found by Dubois is now believed to belong to a different and much younger species.

The small brain, low forehead, heavy brow ridges, protruding mouth, and receding chin give the skull a striking resemblance to that of a great ape, as shown in Fig. 328; yet the brain is far larger than that of any great ape, the tooth line is even, the canine teeth are relatively small, and the dentition is in all respects human rather than simian. There is no longer any doubt that *Pithecanthropus* was human. Unfortunately no limb bones are yet known.

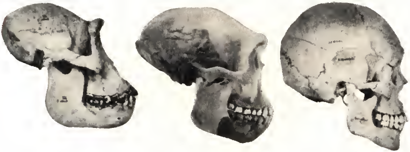


FIG. 328. Skulls of modern gorilla (left), *Pithecanthropus* (center), and modern man (right). The apelike character of *Pithecanthropus* may be seen in the low forehead, heavy brow ridges, protruding jaws, and chinless profile. After F. Weidenreich in *Natural History*.

The geologic date of *Pithecanthropus* was at first thought to be late Pliocene or early Pleistocene, but it is now known to be about Mid-Pleistocene.[1] It is difficult to correlate the deposits in Java with those of a definite glacial or interglacial age because they are in the tropics, far from scenes of glaciation. However, a large fauna of other mammals has now been recovered from the gravel bed that yielded the human fossils, and it clearly indicates a Mid-Pleistocene date.

Six faunal zones are now known in the Pleistocene deposits of Java, and all the remains of *Pithecanthropus* are from a single one of these, the so-called Trinil horizon. Other human remains of more modern type are found in some of the higher zones.

Peking Man. A series of discoveries in 1928 and 1929 near Peking, China, brought to light another race closely allied to *Pithecanthropus* and representing the same stage of human evolution. The remains were found amid cave deposits of Chicken Bone Hill (Chou Kou Tien) about 30 miles south of Peking. At the time of habitation the site was a spacious limestone cavern, but it has since been filled with debris fallen from the walls or washed in from above and cemented in part

with travertine. The race has been named *Sinanthropus pekingensis* (Gr. *Sinos,* China, + *anthropos,* man).

Once the great significance of this primitive human race was perceived, systematic exploration of the deposits was undertaken with the joint support of the Geological Survey of China and the Rocke-

FIG. 329. Model of the skull of Peking man by Franz Weidenreich. Note the low forehead, the heavy brow ridges, the protruding mouth, and the receding chin. About ½ natural size.

feller Foundation, and for more than a decade, 50 to 100 technicians and laborers worked continuously at the excavation. As a result, about 40 individuals have now been recovered, including men and women and children. In addition, a large fauna of contemporaneous mammals has been found, many of which represent the prey that Peking man brought home from the chase. About seven-tenths of all these are deer, suggesting that this was the chief animal hunted.

The human remains (Fig. 329) are nearly all skulls and lower jaws, though a few limb bones have been found. The absence or rarity of other skeletal parts, as well as evidences that each skull had been

broken in a peculiar way before burial, suggests that these are the remains of cannibalistic rites.

As in *Pithecanthropus,* the chin is receding, the forehead very low, the brow ridges over the orbits massive, and the jaws protruding. All these features, and many other technical details, are decidedly apelike characteristics and indicate plainly that Peking man was much closer to our simian ancestors than any modern races. The limb bones prove, nevertheless, that he walked erect. The capacity of the braincase ranges from 850 to 1220 cubic centimeters, but in the three best preserved skulls is about 1000 cubic centimeters (Fig. 329).

Associated with the skeletons have been found charred animal bones and layers with charcoal debris, ranging through a thickness of 20 feet of deposits. It is therefore clear that these people used fire. There have also been found with them more than 2000 crude artifacts of the Chellean cultural type, made from greenstones and vein quartz. These stone implements include choppers, scrapers, gravers, and awls. Some of them were evidently used also for fashioning weapons from animal bones, such as the daggers made from deer antlers. In other words, *Sinanthropus* was already man, and was able to organize his life so as to select intelligently the materials useful for fuel, weapons, and tools, besides being a successful hunter of animals.[2]

Although believed at first to be of Early Pleistocene age, the remains of *Sinanthropus* are now dated by the associated mammals as Middle Pleistocene.

Neandertal Man. Best known of all the extinct species of man is *Homo neandertalensis,* who inhabited the caverns of western Europe during the last interglacial age and part of the last glacial age. The original discovery of this race was made in the Neander Valley near Düsseldorf, Germany, whence the name. Although found the previous year, this remarkable skeleton was first described in 1858, the year before the publication of Darwin's *Origin of Species.* Its striking characteristics and the timeliness of the discovery led to an immediate appreciation of the significance of the Neandertals as a species far more apelike than any living men.

Since 1858, several entire skeletons have been recovered, and incomplete remains of many men, women, and children of the Neandertal race have been found in the caves and rock shelters of Belgium, France, Italy, Spain, Croatia, Crimea, and Palestine. Their stone implements (the Mousterian culture), moreover, are found scattered throughout western Europe and farther eastward in Asia Minor, North Africa, Syria, northern Arabia, Iraq, and even in China. Among the

striking Neandertaloid discoveries of the last few years may be mentioned the skeleton at Broken Hill, Rhodesia; that near Galilee in Palestine; and others at the Cave of the Kids near Mount Carmel, Palestine. From these abundant remains it is possible to present an adequate picture of the racial characteristics and the culture of these interesting people.

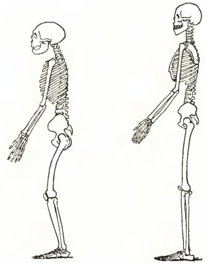


FIG. 330. Skeletons of Neandertal man (left) and that of a living Australian, showing contrast in posture. After Boule, from Woodward, British Museum *Guide to Fossil Man.*

The Neandertals (Fig. 331) were stocky and short of stature, rarely exceeding 5 feet 4 inches. Although they stood upright, their carriage was more like that of a great ape than is that of living man, because the spine lacked the fourth or cervical curvature and the thigh bones were sigmoidally curved in compensation. The head accordingly was carried far forward, and the body had a slouched appearance (Figs. 330, 331). Both hands and feet were large, and the great toe was offset against the rest, as in the great apes.

The head differed from that of modern man in the very low forehead, heavy brow ridges, and receding chin (Fig. 333). The face was undoubtedly big-featured and brutal. Nevertheless the brain was approximately equal in size to that of modern man (1400 to 1600 cubic centimeters), the braincase being low at the front but large in the back and lower part. It has been inferred from the proportions of the brain that the species was deficient in the higher qualities of reasoning and association, and probably less capable than modern man in social organization. It must be remembered, however, that Neandertal man dominated all Europe during the last interglacial age and the early part of the last glacial age, a period estimated to exceed 100,000 years..

The Neandertals made fairly good stone implements, and they also knew how to kindle a fire, for hearths have been found in their cave abodes. In at least two instances the skeletons have been found in their original burial places, where they had been laid away with im-

plements, paints, and food, indicating that the race held a belief in immortality, and buried the dead with ceremonial rites.

Chicago Natural History Museum.

FIG. 331. Old Man Neandertal. Front and side view of a restoration by Blaschke. Note the slouched posture and compare with Fig. 330.

Among the stone implements of these people, the hand ax, scraper, and point are most characteristic. Flint-tipped spears were used, but there is no evidence that Neandertal man used the bow and arrow. In

view of his relatively feeble weapons, it is remarkable that he was a successful hunter of big game, including the bison, cave bear, horse, reindeer, and mammoth, all of which inhabited Europe during his reign.

In his physical make-up, Neandertal man, like the species of the earlier Pleistocene, retained many primitive characteristics pointing clearly to his simian ancestry. He was replaced with relative suddenness by the modern species, *Homo sapiens*, about the middle of the last

American Museum of Natural History.

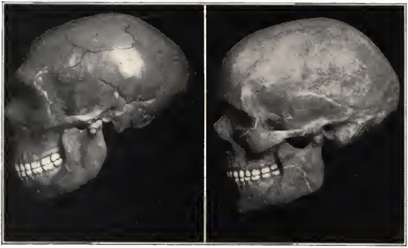
FIG. 332. Skulls of *Pithecanthropus* (left) and Peking man (right), for comparison with those of Neandertal and Cro-Magnon man. From models by Franz Weidenreich.

glacial age, and may have perished without contributing to the modern races of mankind, though it is possible that some existing stocks, like the aboriginal bushmen of Australia, still carry a mingling of Neandertaloid blood.

The Cro-Magnons. Some time during the last glacial age, a superior race of men appeared in southern Europe, quickly replacing the Neandertals. They had high foreheads, well-defined chins, and large brains, and clearly belong to the modern species, *Homo sapiens*. They have been called the Cro-Magnon race for the original discovery of five skeletons at the rock shelter of Cro-Magnon in the French village of Les Eyzies in Dordogne (Fig. 324).

The original find included the skeletons of an old man, two young men, a woman, and a child. Numerous other remains have since come to light, so that the race is now known from many skeletons and associated stone implements and other evidences of culture and art.

Among the notable occurrences is that at Předmost, Moravia, which was a mass burial including fourteen complete skeletons and fragments of others. The ancient camp site at Solutré, France, has also yielded several skeletons besides abundant artifacts and vast numbers of skeletons of the wild animals, chiefly horses, upon which these people fed after the ice had retreated and the reindeer was gone from southern Europe. The caverns of the Dordogne Valley and those



American Museum of Natural History.

Fig. 333. Skulls of Neandertal man (left) and Cro-Magnon man (right), from models by J. H. McGregor.

about Grimaldi on the Italian frontier have likewise yielded numerous skeletons in burial position, with associated artifacts.

Unlike the Neandertaloids, the Cro-Magnons were tall and straight, with relatively long legs, straight thigh bones, and the complete double curvature of the spine that permitted the balance of the head as in modern man. The chin was prominent, the jaws not protruding, the forehead high, and the brain fully as large as in modern races. In physical development the Cro-Magnons were essentially modern (Fig. 333).

In mental development, also, they were superior, for they had abundant and well-formed implements. They used bone for awls and ivory for skewers and ornaments; they made spears and bows and arrows; and they dressed themselves in fur. Their bodies they ornamented with sea shells derived from the Mediterranean and Atlantic coasts,

with fossil shells from places far inland, with the teeth of mammals and even of human beings. Toward the close of the last ice age they made beads and bracelets and other objects of shell and ivory.

Armed with better weapons than any of their predecessors, and with a fuller knowledge of their use, the Cro-Magnons were able to take better advantage of their environment. Thus, they had more

Chicago Natural History Museum.

Fig. 334. The cave of Gargas in southwest France, as restored by Frederick Blaschke, showing a prehistoric artist of the Cro-Magnon race at work on the pictures that ornament the cavern walls. Engravings of elephants and bison may be noted.

ease and time for reflection, and we witness in them the development of art and culture that excite the wonder and admiration of all anthropologists. Besides personal adornment and the use of clothing, this artistic development was expressed in picture writing on the walls of their caves, in sculpture upon fragments of stone or on bone implements, and finally in polychrome paintings like those preserved on the walls of certain caverns in France and Spain (Fig. 334).

The Cro-Magnons were the last of the Paleolithic races in Europe. They appeared during the last glacial age and persisted until the ice sheet had largely wasted away. Their history is divisible into four cultural stages, the Aurignacian, the Solutrean, the Magdalenian, and

the Azilian, each characterized by certain types of flint workmanship. The race was not exterminated like the older human species, for the Cro-Magnon stock, interbred with late migrants from western Asia, is the direct ancestor of living races of South Europeans.

Neolithic Peoples and the Beginning of Civilization

As the last ice sheet disappeared from Europe, the climate moderated and became moister. The reindeer, which had been the chief source of food and clothing for Cro-Magnon man while the ice still occupied northern Europe, now vanished from most of the continent. These changes in climate and food were accompanied by human migrations, as man spread northward in the wake of the vanishing ice. About this time the art of finishing stone implements by grinding and polishing was developed in southern Europe, and a new culture, the Neolithic, spread quickly over the continent. This was accompanied by the development of the art of making pottery, the domestication of animals, and the adoption of habits of communal life. Later on, permanent habitations in the form of stone or wooden huts or tents of skins became general, and agriculture was pursued. In order to secure protection, villages were commonly built on piles over lake shores, swamps, or streams.

With the spread of Neolithic culture, civilization had truly begun, replacing the barbarism and savagery of Paleolithic peoples. There is evidence of this change in human affairs as early as 18,000 B.C. in Asia Minor, Arabia, and Persia. Probably the oldest center of Neolithic culture yet known is the ancient city of Susa in Persia, which is said to date from at least 20,000 B.C.. The culture had spread to the island of Crete by 14,000 B.C. and to Denmark by about 12,000 B.C.

Early Man in North America [3]

All the Paleolithic races of men described above lived in the Old World. It is generally accepted that man evolved in that hemisphere, for no remains of the higher primates are known in America. The date of man's first migration to this continent is a problem long under discussion, but one on which numerous recent finds have thrown light. It now appears certain that he arrived before the extinction of several of the characteristic Pleistocene mammals, notably the Columbian elephant, the American mastodon, a large extinct species of bison, a native camel, three species of horse, and the giant ground-sloth. In-

deed, it has been suspected that he may have contributed to the extinction of some of these great game animals. All the American human fossils are attributable, nevertheless, to the modern species, *Homo sapiens.*

A notable discovery of human bones was made at Vero, south of Daytona Beach, Florida, in 1916, and at Melbourne, about 40 miles farther south. Numerous fragments of human remains occur at the

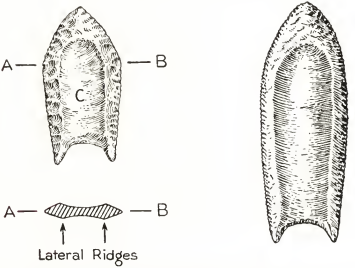


FIG. 335. Folsom points from the Lindenmeier ranch in Colorado, after F. Roberts. The longitudinal fluting (C) of these finely chipped points is distinctive.

latter place in a bed of sand that also contains bones of the giant ground-sloth, two extinct species of horse, the mastodon, the Columbian elephant, and a saber-tooth cat.

In 1926 crude stone implements were found near Folsom, New Mexico, associated with an extinct species of buffalo, *Bison taylori.* Later excavation revealed an arrow point between two bison ribs, and eventually the remains of 40 to 50 specimens of the extinct bison were found within a small area, representing a kill and barbecue. Among these were 16 arrow points of a distinctive type of workmanship now known as the *Folsom culture* (Fig. 335). In recent years this culture has been found widely distributed in southwestern United States, and in several places it is associated with extinct animals. A notable example is the Lindenmeier site north of Fort Collins, Colorado, where, at a depth of 14 or 15 feet below the present surface, the Fol-

som culture is found associated with a "bison kill" similar to that at Folsom. Here the remains of an extinct camel were found with the bison. From this ancient camp site some 2000 stone implements have been recovered, including scrapers, drills, gravers, and blades.

A similar occurrence was found near Plainview, Texas, in 1944,[4] where extensive quarrying in a gravel bed led to the recovery of skeletons of between 50 and 100 bison of an extinct species larger than the modern buffalo. With these were found 19 projectile points and 8 stone scrapers. It is believed that the bison were stampeded into falling from the river bluff. The artifacts resemble those at Folsom. At this quarry the only other animal found was a large wolf, but, near by, the same bed yielded the Columbian elephant and a fossil horse.

Artifacts have also been found deeply buried in river-terrace gravels at numerous localities in southwestern United States, and in several of these they are associated with remains of extinct mammals.

Terraces along Blanco Creek about 100 miles southeast of San Antonio, Texas, for example, have yielded 6 sites in which flint artifacts are associated with bones of extinct animals including elephants, mastodons, horses, bison, camels, glyptodons, etc. Similar deposits at Frederick, Oklahoma, cited in the first printing, should be regarded with skepticism since the artifacts were not seen in place by trained scientists and may not be contemporaneous with the extinct mammals.

The valley about Mexico City has yielded several bits of evidence of early man. A skeleton and associated artifacts were found beneath a lava flow in the suburban village of San Angel, and the same culture was found beneath 10 to 12 feet of sediments northwest of the city. The lava flow is believed to have occurred at least 2000 years ago, and possibly as much as 10,000 years. Hence these people long preceded the Aztecs, who date from about A.D. 500. In 1946 more remains were found near Tepexpan. Here a human skeleton was discovered in a layer that also yielded several artifacts (three gravers, a scraper, and a bone point), as well as bones of the imperial mammoth, bison, horse, and glyptodont.[5]

These are but samples of a large number of occurrences of either artifacts or human fossils associated with the large extinct mammals that were common in North America during the Pleistocene epoch. Such deposits are certainly several thousands of years old, but it is not yet possible to determine whether they are as old as the last glacial age.

In 1931, however, a skeleton was found in varved clays near Pelican Rapids, Minnesota, in circumstances that indicate drowning in a pro-

glacial lake. The skeleton is that of a young woman and was found at a depth of 9 feet, 9 inches, in varved clay. Workmen who exhumed the skeleton assert that the lamination in the clay extended unbroken over it, so that it could not be ascribed to later burial.

It is quite clear, in short, that man arrived in North America several thousands of years ago, probably during the recession of the last ice sheet.

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VI. EPILOGUE

"It is always necessary to close a lecture on Geology in humility. On the ship *Earth* which bears us into immensity toward an end which God alone knows, we are steerage passengers. We are emigrants who know only their own misfortune. The least ignorant among us, the most daring, the most restless, ask ourselves questions; we demand when the voyage of humanity began, how long it will last, how the ship goes, why do its decks and hull vibrate, why do sounds sometimes come up from the hold and go out by the hatchway; we ask what secrets do the depths of the strange vessel conceal and we suffer from never knowing the secrets. . . .

"You and I are of the group of restless and daring ones who would like to know and who are never satisfied with any response. We hold ourselves together on the prow of the ship, attentive to all the indications that come from the mysterious interior, or the monotonous sea, or the still more monotonous sky. We console each other by speaking of the shore toward which we devoutly believe we sail, where we shall indeed arrive, where we shall go ashore tomorrow, perhaps. This shore not one of us has ever seen, but all would recognize it without hesitation were it to appear on the horizon. For it is the shore of the country of our dreams, where the air is so pure there is no death, the country of all our desires, and its name is 'truth.'"

—Pierre Termier.

APPENDIX A

AN INTRODUCTION TO ANIMALS AND PLANTS

Scientific Names. The beginner in natural history is usually dismayed by the scientific names of unfamiliar types of animals and plants, and is inclined to wonder why common names are not used instead. The answer to this is very simple: a name is common only because it is familiar. Such words as *boa constrictor*, *gila monster*, and *rhinoceros* are common, but a small child finds them fully as difficult as *Homo sapiens* (man), or *Equus caballus* (the horse). Moreover, only a few thousand kinds of animals are at all commonly known, and the rest, already exceeding 825,000 kinds, can therefore have no really "common" names.

Furthermore, so long as we have a diversity of languages, there can be no really common names of general and world-wide usage. To the Germans, the common name of the horse is *Pferd;* to the French, *cheval;* to the Italians, *cavallo*, etc. Moreover, a common name such as *bear* has many different meanings; to a New Englander it implies one species, to a Montanan another, and to an Alaskan a quite different kind of bear. Therefore, if naturalists of all countries are to share in scientific studies, it is obviously necessary that each species should bear a name that applies to one kind alone and is recognized in all languages. For such names, naturalists have wisely turned to the classical languages, Greek and Latin.

The early naturalists did, indeed, give each kind of animal but a single name. Thus, in the Roman Empire the cat bore the name *felis*, and the horse was called *equus*. This scheme sufficed so long as only a few hundred kinds of animals were known, and the scholars of the civilized world all lived in a relatively small area about the Mediterranean. But as culture spread during the Middle Ages, and animals from other regions were studied, it became necessary to accompany each name with a short diagnosis or description in order to distinguish it from some similar, previously known kind. Latin scholars at first used the name *felis* for the domestic cat, but they later became acquainted with the great tawny cat of Africa, as well as the spotted cat of the tropics.

When it became necessary to accompany the common name with sufficient adjectives or descriptive phrases to indicate clearly which kind was meant, the great Swedish naturalist, Linnæus, devised the plan of giving each species a double name, the first representing the group (genus), the second a special or specific name for that particular kind. The latter is generally a descriptive or qualifying adjective standing in place of a descriptive paragraph, and, in harmony with the Latin custom, it follows the word which it modifies. Thus, the house cat became *Felis domestica,* and the great spotted cat, *Felis leopardalis* (Lat. *pardalis,* spotted). The scientific name is, therefore, in reality a nickname, or an abbreviation of the longer diagnosis that would otherwise be required.

It should be noted that the generic name is capitalized, and that the specific name is not.

Classification of Animals and Plants. In dealing with any large or complex group of objects, some scheme of classification or orderly grouping is required. To appreciate this fact, we need only contemplate an army of individuals without organization, a great library with the books placed at random on the shelves, or a dictionary with the words arranged by chance! Nowhere is the need for organization more keenly felt than in the study of the enormously varied forms of animal and plant life. Here, obviously, the most useful basis of classification is blood kinship, and a *biologic classification* has therefore been adopted which aims to group creatures according to their degree of actual relationship, regardless of superficial resemblances or differences.

In this biologic scheme, the animal and plant kingdoms are divided, first, into *phyla* (Gr. *phylon,* stock or race), each phylum including organisms that are alike in some fundamental anatomical characters. For example, animals with backbones form the phylum *Vertebrata* (Lat. *vertebratus,* having a backbone); those with jointed legs and bodies, such as insects, spiders, and crabs, form the phylum *Arthropoda* (Gr. *arthron,* joint, + *pous,* foot).

Each phylum in turn is divisible into *classes,* within which the resemblances are still closer. For example, among the vertebrates the fishes constitute one class, birds another, and mammals a third. Classes are further subdivided into *orders.* Thus, the class Mammalia includes the orders *Carnivora* (flesh-eating types), *Rodentia* (gnawers like rats and squirrels), etc. Orders are divisible into *families,* and these in turn into *genera,* each genus including one or several kinds (*species*) of animals that are very closely related and struc-

turally alike. For example, the cats form the genus *Felis,* and the dogs and wolves the genus *Canis.* The species is the next smallest unit, including individuals very closely alike.

Animals

The following table presents in simple form the major subdivisions of the animal kingdom, groups that are wholly extinct being italicized. See also the *Tree of Life,* Fig. 32, p. 57.

A Simple Classification of the Animal Kingdom

Phylum **Protozoa**—single-celled, generally microscopic animals. Ex.: amœba, foraminifera, radiolaria, and many disease germs.
Phylum **Porifera**—sponges.
Phylum **Cœlenterata**—coral-like animals, lacking viscera.
  Class **Hydrozoa**—hydroids, *graptolites.*
  Class **Anthozoa**—corals and sea-anemones, *tetracorals,* hexacorals, *honeycomb corals.*
Phylum **Platyhelminthes**—flatworms (never fossil).
Phylum **Nemathelminthes**—threadworms (never fossil).
Phylum **Trochelminthes**—rotifers, all microscopic (never fossil).
Phylum **Brachiopoda**—brachiopods.
Phylum **Bryozoa**—moss animals.
Phylum **Echinodermata**—echinoderms.
  Class **Asteroidea**—starfish.
  Class **Echinoidea**—sea-urchins, heart-urchins, sand dollars.
  Class **Crinoidea**—sea-lilies or feather-stars.
  Class **Blastoidea**—*sea buds* or *blastoids.*
  Class **Cystoidea**—*cystoids.*
Phylum **Mollusca**—molluscs.
  Class **Pelecypoda**—clams, oysters, scallops.
  Class **Gastropoda**—snails, conchs, etc.
  Class **Cephalopoda**—squids, devilfish, nautiloids, *ammonites,* and *belemnites*
Phylum **Annelida**—segmented worms, earthworms, beach worms, etc.
Phylum **Arthropoda**—invertebrate animals with jointed legs.
  Class **Crustacea**—lobsters, crabs.
  Class **Myriapoda**—centipedes, millipeds, etc.
  Class **Arachnoidea**—spiders, scorpions, *eurypterids, trilobites.*
  Class **Insecta**—insects.
Phylum **Vertebrata** (Chordata)—animals with backbones.
  Class **Pisces**—fishes (actually four classes).
  Class **Amphibia**—salamanders, frogs, *labyrinthodonts.*
  Class **Reptilia**—crocodiles, turtles, *dinosaurs, ichthyosaurs, plesiosaurs, mosasaurs, pterosaurs,* snakes.
  Class **Aves**—birds.
  Class **Mammalia**—milk-feeding, warm-blooded animals (including man).

Phylum Protozoa

Single-celled animals constitute the phylum *Protozoa* (Gr. *protos*, first, + *zoön*, animal), so called on the assumption that it includes the most primitive types of animal life. Although widely distributed and extremely numerous, protozoans are nearly all microscopic and therefore are seldom seen.

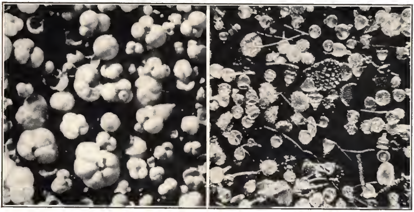
Each protozoan is a tiny droplet of fluid living matter enclosed in a membranous cell wall. Unlike higher animals, it has no special visceral organs for digestion, circulation, reproduction, etc. Food consists of other microscopic creatures, commonly plants, which are swallowed whole. Lacking a mouth, the little animal takes its food through a temporary rupture in its cell wall, and later voids the indigestible residue by the same means. Once in the body, the food particle is attacked by fluids that digest it, and the single-celled animal assimilates this food without the need of a circulatory system. When fully grown, the tiny animal reproduces by simply splitting into two or more young, each of which is like the parent but smaller. Since the parent passes completely into its offspring, *there is no death* in the normal course of events for these simple creatures. Individuals may be killed, of course, by unfavorable environment or by other animals; this, however, may be considered accidental, for death is not the inevitable fate of each individual, as it is with all higher animals.

Although protozoans probably exceed all other types of animal life combined, both in number of individuals and in total bulk, the vast majority are soft-tissued and incapable of fossilization. There are, however, two prolific groups of them that form delicate shells of calcium carbonate or silica, and have left an imposing record. These are the orders Foraminifera and Radiolaria.

The *Foraminifera* (Fig. 336) build tiny chambered shells, commonly of calcium carbonate. They inhabit all the oceans but are rarely found in fresh waters. The majority live on the bottom or cling to seaweeds, but about twenty kinds float near the surface of the open oceans, whence their shells, abandoned at time of reproduction, rain down like a snowfall to cover the sea floor. The commonest of these is *Globigerina*, and the soft, fine-grained, limy deposit made mainly by its shells is known as *globigerina ooze* (Fig. 336). Approximately 50,000,000 square miles of the sea floor are now covered to an unknown depth by these deposits. At various times in the geologic past, foraminiferal shells have accumulated in shallow water to form extensive beds of chalk or limestone. The pyramids of Gizeh, for example, are

made of a limestone that is widely spread in the Mediterranean region and is largely made of coin-shaped shells known as *nummulites* (Fig. 321, p. 494). Still older limestones of the late Paleozoic are formed of *fusulines,* a tribe having shells about the size and shape of wheat grains (Fig. 173, p. 277).

The *Radiolaria* (Fig. 336) make their shells of silica. Differing from the capsule-like shell of the foraminifer, these are of a loose,



Yale Peabody Museum.

FIG. 336. Protozoan shells. Left, globigerina ooze (×10) dredged from a depth of 2898 feet about 100 miles west of Martinique, West Indies. Right, radiolarian ooze (×35) from the Miocene beds of the island of Barbados, West Indies.

open texture, like a delicate glass sieve. They form deposits of radiolarian ooze on parts of the deep sea floor.

Phylum Porifera

The Porifera or sponges are multicellular animals in which there is little specialization of tissues. The "bath sponge" is but the silken skeleton of one highly specialized type. The essential features of the group are better displayed by a very simple sponge (Fig. 337*A*). Such an individual has the form of a slender vase; there is nothing to it but a living *wall* surrounding a large hollow space. This wall is made up of three layers like a jelly sandwich, the outer layer being formed of protective cells (ectoderm), the inner layer of feeding cells (endoderm), and the middle layer of a noncellular jelly-like substance (mesoglea). The endodermal cells feed as do protozoans, each capturing and swallowing other microscopic organisms; the ectodermal cells do not take food but absorb what is needed from the near-by endo-

dermal cells. Thus no digestive or circulatory organs are required.

To strengthen this delicate wall, either mineral spicules or thread-like fibers of spongin, an organic substance allied to silk, are formed in the gelatinous layer. These are secreted by specialized cells and are united to form a loose meshwork. In the bath sponge the spicules are all made of spongin, but in many sponges the spicules are of silica or calcium carbonate (Fig. 337*C*). The mineral spicules are commonly preserved, and some of these, found in the Pre-Cambrian rocks of the Grand Canyon, are among the oldest records of life on the Earth.

FIG. 337. Sponges. *A*, diagrammatic vertical section of a very simple sponge; *B*, similar section of a more complex sponge; *C*, various types of sponge spicules, greatly enlarged. *ect*, ectoderm; *inh*, inhalant canal; *mes*, mesoglea; *p*, wall pore. From Brooklyn Museum of Natural History.

Phylum Cœlenterata

The third phylum of animals includes the *hydroids, corals,* and *jellyfish.* These, like the sponge, consist essentially of a body wall, lacking any internal organs, whence the name Cœlenterata (Gr. *koilos,* hollow, + *enteron,* inside cavity).

Hydroids. *Hydra* is a simple representative of the phylum, and particularly of the class *Hydrozoa.* A vertical section through its slender subcylindrical body (Fig. 338) shows a wall of three layers, as in the sponge. But in three respects it is vastly ahead of the sponge. First, it has muscular tissue that permits change of shape and even locomotion, and makes possible a circlet of muscular tentacles about the mouth with which to capture food; second, in the inner

layer are special gland cells that excrete digestive juices into the central cavity; and, third, it bears stinging cells like those of the jellyfish that can paralyze other animals coming into contact with it. The hydroid is thus able to capture, swallow, and digest animals almost as large as itself (Fig. 338).

Hydras live as solitary individuals, but many hydroids reproduce by budding and thus form colonies of individuals organically united (Fig. 338). Many of these secrete a bell-like or vaselike sheath (hydrotheca) about their body as a protection. These sheaths are formed of chitin, a substance similar to finger nails.

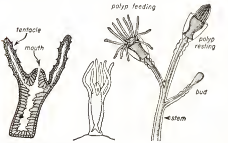


Fig. 338. Hydroids. Left, diagrammatic vertical section of *Hydra*, much enlarged; center, *Hydra* devouring a young trout (×2); right, a colonial hydroid, *Obelia*, with two adult individuals and a young bud.

The *graptolites*, commonly considered an order of hydroids,* lived in early Paleozoic time, forming slender colonies in which individuals were closely ranked along a common axis. They are generally preserved in dark shales where they are pressed flat and reduced to a film of carbon superficially resembling heavy pencil marks on the stone, whence their name (Gr. *graptos*, written, + *lithos*, stone) (Fig. 95, p. 163).

Corals. The corals and sea-anemones form another class of this phylum, the *Anthozoa* (Gr. *anthos*, flower, + *zoön*, animal), so named because of their bright colors and flower-like symmetry (Fig. 339). The coral animal resembles *Hydra* in essentials, but with the addition of thin radial partitions (mesenteries) that extend from the wall part way into the central cavity, subdividing it into a series of alcoves.

The coral animal secretes about its side and base an external skeleton of calcium carbonate. The animal is correctly termed a *polyp*, and its skeleton, *coral*.

For some unknown reason the base of the coral polyp is invariably marked by radial infoldings which alternate in position with the internal mesenteries. The skeleton secreted against this base is marked by radial ridges or plates known as *septa*. Coral polyps may

* Kozlowski has advanced arguments for placing the graptolites with the hemichordates, lowly relatives of the vertebrates.

live singly, but many kinds reproduce by budding new polyps from the margins of the older and thus develop colonies in which many individuals co-operate to build a complex stony skeleton.

The skeleton of a solitary coral may be cushion-shaped or horn-shaped or subcylindrical, and usually has a cuplike depression at the summit in which the base of the polyp is housed. In colonial forms the skeleton is commonly branching or massive, with depressions for the bases of the individual polyps. *The radiating septa are absolutely distinctive of the coral skeleton and serve to distinguish it from all other types of shells.*

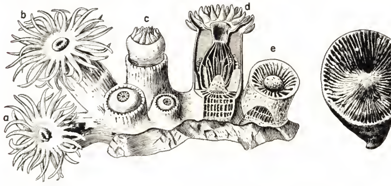


FIG. 339. Left, portion of a colony of a modern coral with living polyps (*a–d*) and an exposed coral showing the septa (*e*); right, a horn coral.

It is well known that corals make reefs in the sea, but only where it is warm and shallow. Accordingly, the coral reefs in the rocks of past geologic ages are regarded as evidence of mild temperature and of shallow water. Corals have been important agents in rock formation at various times in the past. Coral reefs now occupy an area of about half a million square miles of the shallow seas, and their limy debris spreads over a vastly greater area.

Nearly all the modern corals belong to the subclass *Hexacoralla,* so named because their septa are introduced in cycles of six or multiples of six. In these the septa are equally spaced, so that they seem to radiate with regular symmetry in all directions from the center. This group has been the dominant one since the beginning of Mesozoic time. The subclass *Tetracoralla* (Fig. 339, right), on the contrary, which was dominant in the Paleozoic era, shows more or less conspicuous bilateral symmetry, with septa introduced in cycles of four.

Phylum Brachiopoda

The brachiopods constitute a phylum of rather small marine animals that invariably bear an external shell of two pieces, known as valves (Fig. 340). Although between 200 and 300 kinds are now living, they are seldom seen on the beach and are hardly known except to specialists; but they are extremely abundant fossils, especially in Paleozoic rocks, and so challenge the interest of geologists.

The body is much more complex than that of the coral, having a digestive system, kidneys, a nervous system, reproductive organs, and

Fig. 340. Brachiopods. Left, a shell in position of growth, attached to a point of rock by the pedicle. Center, dorsal view of same, showing the pedicle foramen and the bilateral symmetry (i.e., each side is a mirror reflection of the other). Right, side view showing that the valves are unequal in size and in shape.

well-developed muscles. In life, the animal is attached to the bottom by a fleshy stalk (pedicle) at the posterior end, its mouth facing upward. The two valves of the shell are hinged together at the posterior end of the body and can be opened more or less widely at the front. They are borne on the back and front surfaces of the body (not on the sides), and thus a plane of symmetry passes through the middle of each valve. Special muscles open and close the shell, and a pair of interlocking teeth and sockets at the posterior end forms a hinge. A hole (pedicle foramen) for the passage of the stalk is usually present near the apex of the ventral valve.

In so far as the brachiopod shell consists of two valves, it resembles the shell of a clam, but the likeness is purely superficial. The structure of the body is unlike that of a clam, and the shell valves are borne in a wholly different position. In the clam, the valves are on the *sides* of the body and are hinged *along the back;* in the brachiopod, they are borne on the *back* and *front* surfaces and are hinged *across the pos-*

terior end. As a result, the symmetry of the shell is quite dissimilar in these two groups, the brachiopod shell being *inequivalved* although each valve is *equilateral,* each half being a mirror reflection of the other, like the left and right sides of a coat. The clam shell is *equivalved,* right and left valves being mirror reflections of one another (except in deformed types like the oyster), but each valve is *inequilateral,* the front and hind ends being normally different in shape.

Brachiopod shells vary greatly in shape (Pl. 4, figs. 10–22), some being strongly biconvex, others plano-convex, and others concavo-convex, the space between the valves in the last type being so thin that the animal must have had the proportions of a flatworm. In many brachiopods the hinge is short, and the posterior end of the shell pointed or "beaked" as in Fig. 340; in others, it is long and straight, and the shell is "square-shouldered." Some shells are smooth, many are ribbed, and some are spiny. In spite of the diversity of form, *the brachiopod shell is easily recognized by its symmetry.*

Brachiopods are rather small animals, the average length of shell being between 1 and 2 inches. A few attained a diameter of 3 or 4 inches, and the largest that ever lived had a breadth of about 1 foot.

Phylum Bryozoa

The Bryozoa or moss animals form another important phylum little known to the general public, in spite of the fact that living forms are commonly attached to the rocks and seaweeds everywhere along the seacoast (Fig. 341). Anatomically the bryozoan is very simple and in many respects more like a brachiopod than other animals, but, unlike the brachiopod, it is invariably minute and always grows in colonies. The individuals rarely attain a diameter much greater than that of a period on this page, but thousands of them living together may form a colony some inches across. Locally they combine to make reef limestones (Fig. 118, p. 192).

Unlike the brachiopod, the bryozoan forms a simple skeleton in the form of a slender tube or a boxlike cell, with an opening at or near one end through which the front end of the body can be thrust out while feeding. Many bryozoans have only a soft, delicate covering of chitin, but the majority secrete a skeleton of calcium carbonate.

The form of the colonial skeleton varies enormously with different species. It may be branching and mosslike, whence the name (Gr. *bryon,* moss), or stemlike, leaflike, massive, or encrusting. In spite of all this diversity, the bryozoan skeleton is easily recognized because it is made up of minute tubules or cells.

Phylum Echinodermata

The *echinoderms* are peculiarly different from all other animals. This great phylum includes the starfishes, echinoids, crinoids, blastoids, and cystoids. Their bodies are short and commonly globular. Almost all have a radial and five-rayed symmetry. Nearly all develop a shell in the form of limy plates that are secreted in the body

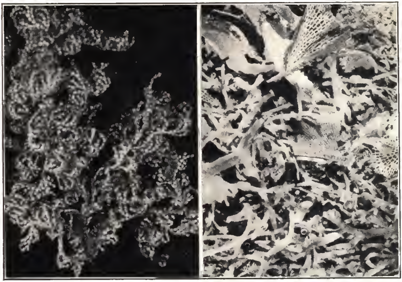


FIG. 341. Bryozoa. Left, *Menipea*, a living colony of mosslike form. Right, fossil bryozoans of many kinds weathering from a piece of Lower Devonian limestone. Natural size.

wall and fit edge to edge like the pieces in a mosaic. The types enumerated above represent five distinct classes which will be discussed in order.

Echinoids or Sea-urchins. A typical echinoid (Fig. 342) has a globular or bun-shaped body bristling with slender, movable spines, whence the name (Gr. *echinos,* hedgehog). The mouth is at the center of the lower side, and the axis of the body is vertical. Stripping away the spines, we find the body wall of the animal to be a rigid, boxlike shell of polygonal plates arranged in twenty vertical columns. Upon these plates are scattered small rounded nubs, each of which was the pivot for a spine.

Radiating from the summit of the shell to the mouth are five paths along which the plates are thickly perforated with small double-

barreled pores. These paths are the food grooves or *ambulacral areas.* In life each pair of pores bears a slender muscular organ known as a *tube-foot.* The tube-feet are part of a remarkable *"ambulacral system,"* found only among the echinoderms, which serves for feeble locomotion, for the gathering of food, and for respiration. The body cavity is spacious and includes a well-developed digestive system, a nervous system, and reproductive organs.

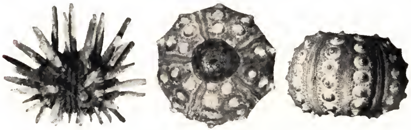


FIG. 342. Three views of the echinoid, *Cidaris.* Left, a young individual as it appears alive; center, upper surface of shell with spines removed, showing the five ambulacral areas (with rows of pores) and five interambulacral areas (with large bosses for spine bases); right, side view showing the arrangement of the plates to be in vertical columns. About ½ natural size.

We have described a typical sea-urchin as a radially symmetrical animal, but there are some specialized types (heart-urchins and sand dollars) in which a secondary bilateral symmetry has modified the primitive, pentameral form. In all echinoids, however, a five-rayed symmetry is clearly evident even though somewhat irregular.

Yale Peabody Museum.

FIG. 343. A primitive starfish, *Devonaster eucharis.* Artificial cast from a natural mold in Middle Devonian sandstone of New York. Natural size.

Starfishes. Next of kin to the echinoids, the starfishes are distinguished by their star-shaped form (Fig. 343), the body being depressed and extended at the sides into tapering rays. The skeleton is made of small limy plates, articulated by fleshy tissues so as to permit some flexibility as in a coat of chain-mail.

Starfishes probably have been abundant since early Paleozoic time, but are rarely found as fossils, because their loosely joined plates fall

apart with the decay of the flesh, and such small irregular plates are not easily recognized.

Crinoids. The crinoids or sea lilies (Fig. 344) look more plant-like than animal-like, for their globular bodies are supported by flexible stalks which anchor them to the sea floor, mouth upward. The animal consists of three chief parts, a *stem*, the *body* proper, and a series of branching *arms*.

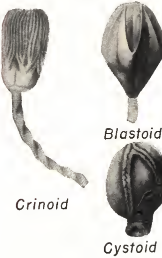


FIG. 344. Stalked echinoderms. A crinoid, *Platycrinus*, with part of its stem; a blastoid, *Pentremites*, without its stem; a cystoid, *Sphærocystites*, with most of its stem missing. Natural size. After Wachsmuth and Springer, Romer, and Schuchert.

In spite of its plantlike appearance, the crinoid is an animal, essentially comparable in its structure to a starfish, though in making this comparison we must turn the starfish with its mouth upward.

The body of the crinoid is covered by a series of limy plates which fit edge to edge like those of the echinoid. These plates are arranged in several horizontal cycles, one above another, beginning at the upper end of the stem. Normally the plates in each cycle number five or some multiple of five, so that five-rayed symmetry is the rule here, as in the sea-urchins and starfish. The stalk is strengthened by the secretion within it of a series of button-shaped limy plates which are superposed like buttons on a string. These "stem joints" are united by muscular tissue, so that the stem has flexibility enough to let the animal swing with the currents. The mouth is at the summit of the body, and from it the food grooves radiate on to the upper sides of the arms. Indeed, the arms are structures developed merely to extend the food grooves.

The living crinoids are brilliantly and beautifully colored with shades of lavender, purple, red, lemon-yellow, or brown, and it is fitting that they should be called sea lilies. They tend to grow in patches on the sea floor and where present are commonly very abundant, so that they present much the appearance of submarine flower beds as they sway gracefully with the bottom currents. Upon the death of the animal its limy plates commonly fall apart. Crinoid remains are

among the commonest fossils in some of the Paleozoic formations, and they give distinctive character to "crinoidal limestones," some of which have wide extent.

Blastoids. The blastoids or sea buds (Gr. *blastos,* bud) form another group of stalked echinoderms (Fig. 344). Their bodies are globular or bud-shaped and are encased in a shell of 13 chief plates of which 3 form a basal cycle, while 2 succeeding cycles have 5 plates each. There are no arms, the food grooves lying upon the surface of the body as they do in the echinoids. These food grooves are always simple, 5 in number, and arranged in perfect five-rayed symmetry about the mouth, which is at the summit. The 5 ambulacral areas are submerged a little below the level of the chief body plates in such a fashion as to give the entire body a superficial resemblance to a flower bud in which the sepals are just beginning to part.

Blastoids are all extinct and are known only from Paleozoic rocks. They were very abundant during only one geologic period, namely, the Mississippian.

Cystoids. The cystoids (Gr. *cystis,* bladder) are primitive echinoderms with globular or almond-shaped bodies but differ from both crinoids and blastoids in that their plates are irregularly arranged, so that the body shows no definite symmetry (Fig. 344). They are extremely varied in details. Some had arms, and others had none; many were stalked, but some apparently were attached directly to the sea floor or were free. They were the most primitive echinoderms.

Phylum Mollusca

This great phylum includes the clams, the snails, the devilfish, the squids, the pearly nautilus, and the extinct ammonites. These commonly possess solid, limy, external shells, and they are generally known as "shellfish." The phylum is an enormous one, with probably no fewer than 50,000 species now living.

Pelecypods (Clams). A typical clam has a laterally compressed body encased in a bivalved shell, the two halves of which *lie on the sides of the body and are hinged along its back.*

The body is generally elongated, and the mouth is at the front end, but there is no distinctly marked head. Lining each valve there is a thin, fleshy extension of the body wall, the *mantle,* which hangs freely about the body like a loose garment. The most conspicuous organs are the great gills, which hang as a double pair of thin plates between the mantle and the sides of the body.

The shell (Fig. 345) is opened by an elastic ligament at the hinge-line, which is placed under tension (or in some cases under compression) when the valves are closed. The shell of most clams is closed by a pair of heavy transverse muscles which run through the animal's body from side to side. Normally one muscle is near the front, and the other near the back end.

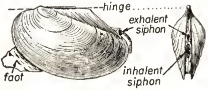


Fig. 345. Pelecypod shell. The common river clam, *Anodonta*, seen from the left side and from the posterior end.

The typical clam is free to creep slowly about by thrusting out the ventral edge of its muscular body wall, which serves to draw the animal along. Secondarily, many clams have given up this freedom and lie on one side and adhere to the bottom, as does the oyster, or attach themselves to the rocks by silken threads, as does the blue clam. Still others burrow in the mud or even in hard rock.

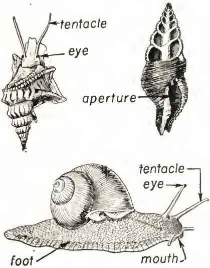


Fig. 346. Gastropods. Upper right, empty shell with front side of spire cut away; upper left, another shell with the snail crawling upward on the page, the head, with eyes and tentacles, showing above the shell; below, a common land snail in crawling position with creeping "foot" extended and shell coiled over the back. After Hatschek and Cori.

The clam shell, like that of all other molluscs, consists of three layers. The outer one is a film of organic material to protect the limy part of the shell from solution. The second layer is of calcite and commonly has a white, porcelain-like appearance, while the inner layer is made of aragonite or mother-of-pearl and has the iridescence of pearl. In fact, the precious pearl is a secretion formed between the mantle and the shell, usually in an attempt by the animal to protect itself against a parasite or other irritant.

Gastropods (Snails). Though fundamentally like the clam in many of its anatomical structures, the snail is in several ways more highly specialized. It has an elongate

muscular body with a distinct head bearing a pair of eyes and a pair of tentacles or feelers. Its mouth is provided with a flexible rasping tongue whereby it can shred either plant or animal food; it is therefore not dependent on microscopic objects. As a result its gills are small and plumelike, since they are used only for respiration. Internal organs resemble those of the clam in most respects.

The shell of the snail is coiled spirally and consists of a single valve. As in the clam, the shell is secreted by a mantle, so that the body may be measurably free.

When disturbed, the snail can withdraw completely into its shell, but normally it extends most of its body and creeps about, carrying the shell upon its back (Fig. 346). The ventral surface of the body has developed into a muscular creeping sole, whence the group is known technically as the *Gastropoda* (Gr. *gaster,* stomach, + *pous,* foot).

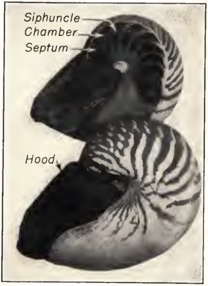


FIG. 347. Cephalopods. The pearly nautilus in its shell. The lower shell is intact, but the upper one has the left side cut away to reveal the hollow chambers separated by curved septa and connected by the tubular siphuncle.

Most commonly the gastropod shell is coiled in a helicoid (corkscrew-like) spiral, but many fossil forms are bilaterally symmetrical like a watch spring. Rapidly expanding shells have few volutions, but slowly expanding ones commonly have high slender spires. The shell may be ornamented with spines, ribs, or nodes.

Cephalopods. The squids and devilfish represent a class of molluscs that has been abundant and important in all the seas since early Paleozoic time. Unlike the sluggish snails and clams, they are active, alert, and aggressive. With their keen eyesight and strong powers of swimming, they alone of all invertebrates are able to compete actively with the vertebrate animals of the seas. The living *giant squid* is the largest invertebrate animal of all time.

The name cephalopod (Gr. *cephale,* head, + *pous,* limb or foot) was suggested by the fact that all members of the class bear a circlet of fleshy limbs about the mouth, which is at the front of the head.

The squid and devilfish are shell-less, but the pearly nautilus (Fig. 347) bears an external chambered shell, as did a host of forms known only as fossils. Here, then, are living examples of the two great subclasses of cephalopods. The first is represented by the squids, whose only shell is vestigial and internal; the second by the nautilus with its external, chambered shell. Obviously the shelled cephalopods are of chief interest to the geologist, since they alone are ordinarily preserved as fossils.

The cephalopod shell has essentially the form of a slender cone, which may be straight or coiled (Fig. 106, p. 177). If coiled, it is almost invariably in a flat spiral like a watch spring. The animal's body occupies only the larger end of the shell, the rest having been partitioned off into a series of chambers by transverse plates known as septa. In the living nautilus (and presumably in extinct types) the chambers are filled with gas and thus serve to buoy up the animal and its shell.

The chambers represent successive portions of the shell that were vacated as the growing body moved forward; and the partitions or *septa* are walls secreted against the bluntly rounded posterior end of the body to give it support after the animal has moved forward. These partitions are attached to the inner surface of the shell, and the line of junction is known as a *suture*. The form of the sutures and the course which they take in the shell are of great importance in the classification of the cephalopods. Since the septa are formed within the shell, the *suture is not visible externally, but in fossil forms where the chambers have been solidly filled with mineral matter and the outer shell then dissolved away, the sutures show clearly as sharp lines on the fossil* (Fig. 106). The animal retains connection with the abandoned chambers by a slender tube, the *siphuncle*, which runs back through all the septa. *Septa and a siphuncle are absolutely distinctive features of the cephalopod shell* and serve to distinguish it readily from that of the snail.

Nearly all the primitive cephalopods had straight shells (Fig. 104, p. 174), which, to an animal swimming backward, presented obvious disadvantages. Curved, loosely coiled, and tightly coiled shells were developed in order, and the forms with straight ones eventually became extinct. Besides being compact, the coiled shell brings the supporting gas chambers directly above the center of gravity, so that the animal can float at ease in the water.

Nautiloids. The shelled cephalopods are further divisible into two great orders. In the first the septa were simple, saucer-shaped plates

secreted against the smoothly rounded posterior end of the animal's body. In these, of course, the sutures run directly around the shell as simple lines without marked flexures (Fig. 106), as in the nautilus (Fig. 347). This order has been named, accordingly, the *Nautiloidea.* The pearly nautilus is their only living representative.

Ammonites. The ammonites, cousins of the nautiloids, also bore chambered shells; but in these the septa were fluted or ruffled near their edges, and as a result the sutures form strongly crenate lines around the shell. In the earliest ammonites the fluting of the septa was very slight, and each suture showed only a few simple bends (Pl. 8, figs. 9, 12), but gradually the fluting became highly complex, and the suture lines accordingly assumed a complicated form (Pl. 14, fig. 11).

Belemnites. The belemnites (Fig. 228, p. 357) were squidlike cephalopods that lived only during the Mesozoic. They possessed a conical chambered shell like that of a primitive straight-shelled nautiloid, but it was internal, having been overgrown completely by flesh (Pl. 14, fig. 8).

Squids are closely related to the belemnites, but in the former the shell (also internal) is reduced to a mere vestige (the "pen").

Phylum Arthropoda

The insects represent a phylum of animals characterized by jointed walking legs, whence the name *Arthropoda* (Gr. *arthron,* joint). Other examples are the spiders, scorpions, lobsters, and crabs, and some important fossil groups such as the trilobites and eurypterids. All these have segmented bodies and jointed limbs. Their bodies are protected by a neatly fitting jointed armor made of chitin. In some, like the lobster and crab, this skeleton is strengthened by the addition of calcium carbonate. This is undoubtedly the largest and most diversified phylum in the animal kingdom.

Insecta. The insect possesses an elongate, bilaterally symmetrical body distinctly divided into head, thorax, and abdomen. The sharp constriction separating thorax and abdomen, as in the wasp, has suggested the group name (Lat. *insectus,* cut into). The abdomen is without limbs, but the thorax bears three pairs of walking legs and commonly two pairs (in one order, one pair) of wings. The head bears a pair of compound eyes and a pair of slender feelers or antennæ. The mouth is provided with specialized biting or sucking devices. The physical senses are rather highly developed.

Insects are too easily destroyed to be commonly preserved as fossils, but locally they are found as far back as the late Paleozoic (Fig. 192, p. 302).

Crustacea. The lobster and crab represent another great class of the arthropods, but, unlike the insects, these, and nearly all their kin, live in the water and breathe by means of gills. The name *Crustacea* (Lat. *crusta,* crust) refers to their hard, crustlike armor, but it must be confessed that many examples of the class do not have a hard shell.

In most Crustacea each of the segments of both thorax and abdomen bears a pair of jointed appendages (in some forms, part or all of the abdominal segments lack appendages). Commonly those on the thorax are walking legs (as in the lobster), and those on the abdomen are for swimming, but in many of the primitive Crustacea all the limbs are flattened swimming paddles. The gills are generally plumose and are attached to the legs.

Arachnoidea. Spiders and scorpions belong to a class of arthropods known as the Arachnoidea (Gr. *arachnes,* spider). The head of a spider is fused to the thorax to form a cephalothorax, which is separated from the abdomen by a deep constriction and bears four pairs of walking legs. The abdomen is not segmented. The head bears several simple eyes but nothing like the compound eyes of the insect. Also it does not bear antennæ. The ability to spin a web is a characteristic feature of the spider. Spiders, being soft-bodied, are rarely preserved as fossils, but specimens found in the Lower Devonian rocks of Scotland are among the most ancient records of land animals.

The *eurypterids* or "sea scorpions" (Figs. 122, 123, pp. 199, 200) were a remarkable race of large aquatic arachnids closely resembling the scorpions in bodily form. Indeed, they were almost certainly the direct ancestors of the scorpions. The eurypterids were confined to the water, and chiefly marine waters, and their limbs were partially modified into swimming paddles. They were relatively large, the average length being several inches. One form, *Pterygotus,* from the Silurian rocks of New York State, had a length of about 9 feet and ranks as the largest arthropod of all time. The eurypterids are common and striking fossils in certain middle Paleozoic formations, but the race died out before the close of the Paleozoic era.

Trilobites (pronounced *trī'lō·bīte*) formed a primitive but exceedingly important group of arachnids which is now extinct and is known

only as fossils from the Paleozoic rocks. In these the body was depressed and distinctly divisible into head, thorax, and tail (Fig. 82, p. 143). Head and tail were each covered by an unsegmented shield, but the thorax was jointed. The entire body was longitudinally trilobed by reason of a pair of grooves that separated a rounded central axis from the lateral areas. *This trilobation is* at once *the most distinctive feature of the group* and the one which gave it the name *Trilobita*.[1]

The trilobites usually possessed a pair of compound eyes and a pair of antennæ or feelers. Each body segment bore a pair of legs, and these were essentially alike from head to tail. Each leg consisted of two branches, the lower one of which was a jointed limb for crawling, while the upper and outer branch was a delicate, feather-like structure, commonly regarded as a gill.

Phylum Vertebrata

The most advanced of all animals are those possessing a vertebral column or backbone. So important is this phylum that it is often contrasted with all the other animals, which are known collectively as *invertebrates*. The vertebrates are characterized by the highly organized character of their nervous system, with the spinal cord running along the dorsal side of the body, and by many other important details, but *the possession of a backbone is the most obvious and distinctive character*. There are eight distinct classes, as follows: *fishes* (four classes), *amphibians*, *reptiles*, *birds*, and *mammals*.

Fishes. Fishes are *primitively aquatic, cold-blooded vertebrates that breathe by means of gills.* Most of them possess paired lateral fins as well as a tail fin.

This is an enormous and highly diversified group with a long geologic record and, although commonly treated as a single class, is now subdivided into four distinct classes. Many are scaled, but several of the extinct groups bore an armor of bony plates and some (for example, the catfish) are not protected by either scales or bone. The skeleton is made of bone in the majority of modern fishes, but in most of the early groups it consisted of cartilage, as in the modern sharks and sturgeon.

It is important to distinguish between the fishes, which are primitively adapted to life in the water and breathe by means of gills, and, on the other hand, certain fishlike animals that have returned from the land to become secondarily adapted to the water. Among the latter are whales, porpoises, and seals, and certain extinct reptiles

(ichthyosaurs, plesiosaurs, and mosasaurs). These secondarily aquatic animals breathe only by means of lungs and must come to the surface for air. They mimic fish but are not closely related to them.

Amphibia. The frogs and salamanders constitute a class of vertebrates that are only partially adapted to life on the land and have many features to remind us of a fishlike ancestry. Indeed, they are certainly the most primitive class of land vertebrates, and they clearly evolved from fishes. The salamander is a typical representative of

FIG. 348. A typical reptile, the Florida alligator.

the class (the frog being a modern and extremely specialized form). Because its members live partly in water and partly on land, the class has received the name Amphibia (Gr. *amphi,* on both sides, + *bios,* life). *The metamorphosis from an aquatic youth (tadpole) to a terrestrial adult life distinguishes amphibians from all other land animals* (Fig. 35, p. 61).

Reptiles. The reptiles constitute a very large class of vertebrates and one that for long geologic ages completely dominated the Earth. The group includes the alligators (Fig. 348), crocodiles, lizards, turtles, and snakes, and the extinct dinosaurs and pterosaurs. The crocodile is a very typical reptile.

Reptiles are cold-blooded, egg-laying animals. In shape, many of them closely resemble an amphibian, but they all differ from the amphibians in the way the young develop. The reptile lays its eggs on the land, that is, out of the water. These are provided with stored-up food in the form of yolk so that the young can develop fully enough

to crawl about and care for themselves immediately upon hatching. In other words, the reptiles are completely adapted for terrestrial life.

Although united by such features as their cold blood, their egg-laying habit, and various details of skeletal structure, the many different stocks of reptiles specialized greatly; some returned secondarily to aquatic life, and one group, the extinct pterosaurs, had wings.

Birds. The birds constitute a very well-defined class of vertebrates characterized by the presence of feathers and warm blood and by the egg-laying habit. In them the front limbs are specialized as wings. The birds diverged from one group of reptiles at about the same time the mammals were developing from another.

Mammals. The mammals are warm-blooded. They bring forth their young alive and nourish them with milk. All of them bear hair, though in some, as the whale and the elephant, the hair is almost lost through specialization. They constitute the dominant group of land animals of the Cenozoic and modern worlds, and some (seals, porpoises, and whales) have secondarily returned to the sea.

One small aberrant group, the monotremes, lays eggs. Two living genera are believed to represent an ancient, primitive stock of the mammals, but no paleontological record of this group is known.

The mammals did not appear on the Earth until Mesozoic time, and there is clear evidence that the ancestral types descended from one of the primitive groups of reptiles.

Plants

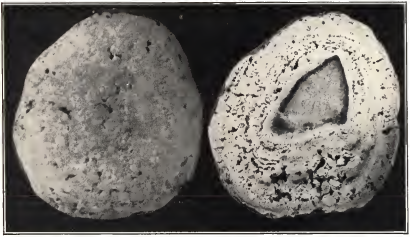
A Simple Classification of the Plant Kingdom (after Berry, 1920)

Phylum **Thallophyta**—bacteria, fungi, seaweeds, etc.
Phylum **Bryophyta**—moss plants.
Phylum **Pteridophyta**—ferns.
Phylum **Arthrophyta**—scouring rushes, *calamites, sphenophylls.*
Phylum **Lepidophyta**—club mosses, "ground pine," *lepidodendrons, sigillarias.*
Phylum **Pteridospermophyta**—*seed ferns.*
Phylum **Cycadophyta**—cycads, *williamsoniellas, cycadeoids.*
Phylum **Coniferophyta** (gymnosperms)—*cordaites,* pines, sequoias, gingkos.
Phylum **Angiospermophyta**—flowering and fruiting plants, hardwood trees, etc.

Phylum Thallophyta

Plants of simple structure, such as bacteria, fungi, and seaweeds, are embraced for convenience in a single phylum, the Thallophyta (Gr.

thallos, young shoot, + *phyton*, plant), so named because of their soft, nonwoody nature. The *bacteria* are single-celled, microscopic, and soft-tissued. *Diatoms* are aquatic plants, likewise single-celled and microscopic, which live in vast numbers near the surface of the seas and lakes and form one of the chief sources of food for all the marine animals. They secrete delicate siliceous shells which accumulate over large areas of the modern ocean floor as *diatom ooze.*



Yale Peabody Museum.

FIG. 349. Calcareous algæ. A "water biscuit" from the bed of Little Conestoga Creek, near Philadelphia, Pennsylvania. Left, external view of the colony; right, a median section showing the concentric laminæ of algal deposit about an angular pebble. Slightly less than natural size.

Plants probably evolved in the water and developed there for long ages before they could adjust themselves to the conditions upon the land. This is inferred, at least, from the fact that nearly all the thallophytes are still aquatic plants. Some of the seaweeds attain a length of 100 feet, but, regardless of size, these plants have no woody tissue and no circulatory system, for they lack the vascular tissue that serves to conduct the sap in higher plants and at the same time forms woody growth. It is for this reason that they can not successfully leave the water. All those forms that do live on land, such as fungi and lichens, are small, and grow only where there is considerable moisture. All the thallophytes have a simple system of reproduction by means of spores.

Most of the thallophytes are poorly adapted for preservation as fossils. A number of types of the algæ, however, cause the precipitation of calcium carbonate, which settles over them to form a limy deposit. Figure 349 shows such a deposit (a "water biscuit") formed by a mold-like colony of microscopic blue-green algæ that covered a pebble in a stream bed. The deposit has a finely laminated texture due to the addition of concentric films of the calcium carbonate. Similar limy deposits (Figs. 71, 72, pp. 124, 125) occur in rocks of all ages as far back as the Archeozoic, and include the very earliest direct evidence of life on the Earth.

The calcareous algæ play a very important role in the formation of modern "coral reefs," commonly depositing as much as 25 per cent of the reef.

Phylum Bryophyta

This small phylum, including the mosses and liverworts, represents the simplest stage of adaptation to land life. Like the thallophytes, these plants lack vascular tissue, hence remain very small and thrive only in moist places. Almost nothing is known of them as fossils.

Phylum Pteridophyta

The great tribe of the ferns constitutes the phylum Pteridophyta (Gr. *pteris*, fern). They are the simplest of plants to be well adapted to land life. They have well-developed vascular tissue and are differentiated into roots, stem, and leaves. Whereas many of the ferns are small and herbaceous, the tree ferns of the tropics have woody trunks and commonly reach a height of 20 to 50 feet, bearing a crown of large fronds. Ferns are distinguished above all else by the fact that *they reproduce by means of spores borne on the under sides of the leaves or on slightly modified leaves*, never in cones.

Ferns are among the oldest fossil land plants known, being recorded first in the Lower Devonian rocks. They have been a prolific tribe in all subsequent ages.

Phylum Arthrophyta

The scouring rushes and their kind constitute a well-defined tribe characterized by regularly jointed stems, whence the name (Gr. *arthron*, joint). The existing horsetail or scouring rush (*Equisetum*) grows abundantly in moist places in many parts of the country. In all the arthrophytes the stem has only a thin cylinder of woody tissue

around a large center of pith. Reproduction is by means of spores which are borne in strobili (cones) at the tops of the stems.

Modern arthrophytes are mostly small, and the race is decadent, having passed its climax in the late Paleozoic, when giant scouring rushes (calamites) grew to the height of trees and had stems as much as 12 inches in diameter (Figs. 165, 166, pp. 268, 269).

Phylum Lepidophyta

The *scale trees* or lepidophytes (Gr. *lepis,* scale) constitute another well-defined tribe of plants that occupy a humble place in the modern world but were very important in the Paleozoic forests (Figs. 165, 166, pp. 268, 269). The ground pines or club mosses are modern examples. Like the arthrophytes, these plants bear spores in strobili at or near the tips of the stems.

Many of the Paleozoic species attained the size of forest trees. In these the leaves, when shed, left prominent scars regularly spaced over the bark of the trunk and limbs (Fig. 167, p. 270). The name lepidophyte refers to these characteristic markings.

Phylum Pteridospermophyta

The oldest and most primitive seed-bearing plants were fernlike in everything but their fruit, whence the name (Gr. *pteris,* fern, + *sperma,* seed). They are commonly known as *seed ferns.*

The distinction between the spore-bearing and seed-bearing plants is comparable to that between the egg-laying and the viviparous animal, both in its nature and in its significance. The egg is a simple cell, deposited to hatch into an embryo that must look out for itself at a very immature stage of its development; the spore, likewise, is a single cell cast free to generate and grow as best it can. On the other hand, the viviparous animal retains the egg in the mother's body until it has developed into an embryo of considerable complexity before birth liberates it to shift for itself. Similarly, the seed is an embryo plant formed after the fertilization of the ovum, which is retained and nourished by the mother plant until considerable size has been attained and food is stored up to give the new plant a good start in life. The development of seed is a very considerable specialization. That it was an obvious advantage is suggested by the dominance of seed-bearing plants on the modern lands.

The seed ferns were common from the late Devonian to the end of the Paleozoic, when they died out, having given rise meanwhile to other phyla of seed-bearing plants.

Phylum Cycadophyta

The living sago palms or cycads represent an extensive tribe, mostly extinct, which has particular interest as the probable connecting link between the seed ferns and all higher plants, especially the true flowering plants (angiosperms). It is a great phylum, divisible into two well-marked orders, the one (*Cycadeoidea*) entirely extinct, and the

G. R. Wieland.

Fig. 350. Stems, foliage, and flowers of the cycadeoid, *Williamsonia*. Lower Jurassic of Mexico. Natural size.

other (*Cycadales*) represented by the modern cycads. The cycads (Fig. 217, p. 347) possess short trunks and large pinnate leaves, and bear seeds in loose cones. The trunk is heavily armored with persistent leaf bases.

The cycadeoids (of late Paleozoic [?] and Mesozoic age) bore conspicuous flowers. They were of two chief types, one stocky, like the modern cycads, and the other slender and branching. The branched cycadeoids are of the greater interest from the evolutionary point of view. They possessed rather slender stems bearing flowers at forks (Fig. 350). It is believed that these plants developed from seed ferns and on the one hand evolved into the thick-bodied cycadeoids and on the other were at least closely allied to the early angiosperms. This

group of cycadophytes is abundantly represented in the Triassic and Jurassic and probably was present in the late Paleozoic.

Phylum Coniferophyta

The conifers constitute another great tribe of rather primitive seed plants characterized by the development of cones and, generally, by evergreen foliage. The leaves are as a rule needle-like or straplike and have parallel veins. There are several orders. The pines are typical.

The oldest group of conifers is the *cordaites,* which were common in the forests from Devonian to Permian time. Unlike the later conifers, they had large, straplike leaves, and their seeds were loosely arranged in racemes instead of cones.

Other groups, including the pines, araucarians, and gingkos, are known throughout the Mesozoic and later periods.

Phylum Angiospermophyta

The most advanced of all plants are the hardwood trees and the true flowering plants, included in the phylum Angiospermophyta, of which at least 125,000 kinds have been described. They are all, of course, seed-bearing, but show a great advance over the other seed-bearing phyla in that their seeds are protected in a closed capsule or ovary. For this reason they are known as angiosperms (covered seed) in contradistinction to the gymnosperms (naked seed), which include the seed ferns, conifers, and cycads.

The angiosperms are commonly characterized as *the flowering plants,* but this is hardly justified, since even the conifers and cycadophytes have flowers of a sort, and many of the latter had large and complicated flowers probably rivaling in size and brilliance the best of the angiosperms.

The angiosperms are first identified in the Lower Cretaceous rocks, where the characteristic net-veined leaves of deciduous trees make their appearance.

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Appendix B

CORRELATION TABLES

The following tables indicate the age relations of selected rock formations. Horizontal lines mark beds of equivalent age. The space allotted to a rock unit indicates the relative time it represents, and has little relation to actual thickness. Vertical shading indicates a hiatus.

Series	Central Appalachians	Southern Appalachians	Upper Miss. Valley	East-central Nevada	Central Wyoming	Canadian Rockies
Craixian	Conococheague ls.: Gatesburg f Warrior f.	Copper Ridge dol. Maynordsv. ls. Nolichucky sh	Trempeleau stage Franconia stage Dresbach stage	Mendha ls.	Boysen f.: Grove Cr member Snowy Range member Maurice member	Goodsir f Sabine f. Bosworth f.
Albertan	Elbrook f.	Canasauga sh.: Maryville ls Rogersville sh. Rutledge ls.		Highland Pk Burrows dol Peasley ls Chisholm sh Lyndon ls. Comet sh.	DePass f.: Gros Ventre member Flathead m	Eldon dol. Stephens f. Cathedral d. Ptarmigan f.
Waucobian	Waynesboro f. Tomstown dol. Antietam qtz.	Rome f. Shody dol. Weisner qtz.		Pioche sh. Prospect Mt qtz.		Mt Whyte f. St. Piron ss.

TABLE 1. Cambrian Formations.

Series	New York State	Central Appalachians	Central States	Western States
Cincinnatian	Queenston sh. Oswego ss. Pulaski sh. Whetstone Gulf sh.	Juniata ss. Bold Eagle congl. "Oswego" ss. Reedsville sh. Martinsburg sh.	Richmondian stage Maysvillian stage Eden sh.	Bighorn dol.
Champlainian	Utica sh. Trenton ls. / Canaj sh. Chaumont ls. Lowville ls. Pamelia ls. Chazy ls.	Coburn ls Salona ls Nealmont ls. Hunter ls / Edinburg ls. Hatter ls Lincolnshire ls. N. Market ls. / Blackford	Viola ls. / Galena dol. Simpson gr.: Bromide ls, Tulip Cr. f, McLish f., Oil Cr. f, Joins f. St. Peter ss.	Eureka qtz. Swan Pk. qtz.
Canadian	Beekmontown dol. and ls. Deepkill sh.	Bellefonte dol. Axemann ls. Nittany dol. Stonehenge ls. / Chepultepec ls. "Beekmantown" dol.	Black Rock ls. Smithville ls. Powell dol. Cotter dol Theodosia f. Roubidoux f Gasconade dol. Arbuckle ls.	Ellenberger El Paso ls. Garden City ls.

TABLE 2. Ordovician Formations.

Series	New York State	Great Lakes Region	Central Appalachians	Ohio and Tenn. Valleys
Cayugan	Manlius group Cobleskill ls. Salina group: Bertie ls., Camillus sh. and salt, Vernon sh.	Bass Id. group Salina sh	Keyser group Tonoloway ls. Wills Creek sh. Bloomsburg redbeds	
Niagaran	Guelph dol Lockport dol Clinton group: Rochester sh, Irondequoit ls, Reynales ls., Thorold ss.	Guelph dol. Engadine (Racine) dol. Manistique dol. Burnt Bluff gr.: Hendrix dol., Byron dol.	McKenzie f. ? ? Clinton group: Rochester sh, Keefer ss., Rose Hill sh Shawangunk congl.	Huntington dol. / Peebles / Durbin Louisville / Brownsport Osgood / St. Clair
Medinan	Grimsby (Albion) ss. Cabot Head sh. Whirlpool ss.	Mayville dol. Monitoulin dol.	Tuscarora ss.	Brassfield ls.

TABLE 3. Silurian Formations.

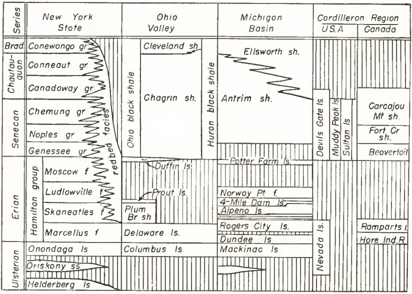

Table 4. Devonian Formations.

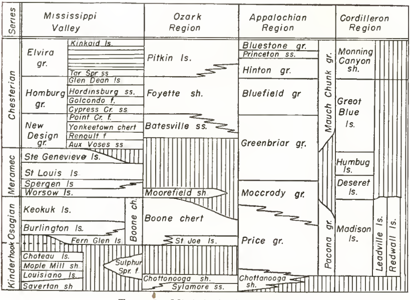

Table 5. Mississippian Formations.

Series	Mid Continent: Kansas	Mid Continent: Oklahoma	Mid Continent: Texas		Illinois & Kentucky		Appalachian Region	
Virgilian	Wabaunsee gr Shawnee gr Douglas gr	Vanoss f. Ada f. Vamoosa f.	Cisco	Thrifty gr. Graham gr.			Monongahela	Waynesboro coal Pittsburgh coal
Missourian	Pedee gr. Lansing gr Kansas City gr Pleasanton gr.	Ochelata f Francis f. Seminole ss.	Canyon	Caddo Cr gr Graford gr Whitt gr	McLeansboro	La Salle ls Lonsdale ls	Conemaugh	Ames ls. Brush Cr. ls.
Desmainesian	Marmaton gr. Cherokee sh	Holdenville f. Wewoka f Wetumka sh Boggy f. Savanna f.	Strawn	Lone Camp Millsap Lake gr	Carbon.	Herrin coal Stonefort ls.	Allegheny	U. Freeport ls. Clarion coal Brookville coal
Atokan		McAlester sh Hartshorne ss Atoka f.	Lampasas	Smithwick gr Big Saline gr	Tradewater	Seville ls.	Pottsville	Kanawah gr
Morrowan		Wapanucka ls. Johns Valley sh Jackfork ss Stanley sh	Morrow	Marble Falls ls.	Caseyv.			New River gr Pocahontas gr.

TABLE 6. Pennsylvanian Formations.

Series	Glass Mts. Texas	Guadalupe Basin Texas	Grand Canyon	Wyoming	Central Texas
Ochoan	Tessey ls.	Dewey Lake redbeds Rustler dol + anhydrite Salado halite Castile anhydrite			
Guadalupian	Gilliam ls. Capitan reef Altuda f. Vidria member Word f.	Delaware Mt. gr.: Bell Canyon f., Cherry Canyon f., Brushy Canyon f. Capitan reef Carlsbad ls. Chalk Bluff f. Goat Seep reef		Phosphoria f. L. Chugwater redbeds	Whitehorse group
Leonardian	Leonard f. Hess facies	Cutoff sh. Victoria Peak gray ls Bone Spring ls. (block ls.)	Kaibab ls Toroweap ls. Coconino s. ?		Pease R. gr: Blaine gyp Clear Fork gr: Choza f, Vale f., Arroyo f. Wichita gr.: Belle Pl.
Wolfcamp	Wolfcamp f.	Hueco ls.	Supai f. ?	Cassa gr. Lyons Owl Cr	Wichita gr.: Admiral f., Putnam f., Moran f., Pueblo f.

TABLE 7. Permian Formations.

Series	European stages: Alps	European stages: Germany	Appalachian Region	Colorado Plateau	Wyoming	Central Nevada	California	West Canada
Upper Triassic	Rhaetian	Keuper series	?	?		?		
	Norian		Newark gr	Chinle f.		Gabbs f.	Brock sh.	Schooler Cr f.: Pardonet
	Kornian		?			Luning f	Hosselkus ls.	Gray m.
Middle Triassic	Ladinian	Muschelkalk ser.				?	Pit sh.	
	Anisian					Excelsior f.		Spray River f.: Whitehorse m.
L. Triassic	Scythian	Bunter series		Moenkopi f	Upper Chugwater sh; Dinwoody f	Candelaria	Dekkas volcanics	Sulphur Mt.

TABLE 8. Triassic Formations.

Series	European Stages	Wyoming	Colorado Plateau	Alberta and B.C.	Central Oregon	California
Upper Jurassic	Purbeckian				Lonesome f.	Knoxville gr
	Portlandian					Franciscan gr.; Mariposa sl
	Kimmeridgian	Morrison f.	Morrison f.			
	Corallian		San Rafael gr.: Summerville f.		?	
	Oxfordian	Sundance f.	Curtis f.	?		
	Callovian		Entrada ss; Carmel f.	Fernie sh.	Trowbridge f.	
Middle J.	Bathonian	Gypsum Spr f.			?	
	Bajocian				Izee gr.; Colpitts gr.	
Lower Jurassic	Toarcian		Glen Canyon gr.: Navajo ss.		Mowich gr.	
	Pliensbachian					
	Sinemurian					
	Hettangian		Kayenta f.; Wingate ss			

TABLE 9. Jurassic Formations.

Series	European stages	Texas	Western Interior	East Gulf Coast	Atlantic Coast
Upper Cretaceous		Gulf series	Laramie group		
	Maestrichtian	Navarro gr.	Montono group: Fox Hills ss; Bearpaw sh.	Ripley sh.	Monmouth gr.
	Campanian	Taylor gr.	Montono group: Belly R. f.: Judith R; Claggett sh; Eagle ss; Pierre sh.	Selma chalk	Matawan gr.
	Santonian			Coffee ss	
	Coniacian	Austin chalk	Colo. gr.: Niobrara chalk	Eutaw f.	Magothy f
	Turonian	Eagle Ford sh	Colo. gr.: Benton sh		
	Cenomanian	Woodbine ss.	Dakota ss.	Tuscaloosa f.	Raritan f
Lower Cretaceous	Albian	Comanche s.: Washita gr.; Fredericksburg gr.	Fusan sh; Lakato ss		Patapsco f
	Aptian	Trinity gr.			
	Barremian				
	Hauterivian				Arundel f.
	Valangian				
	Berriasian				Patuxent f.

TABLE 10. Cretaceous Formations.

Series	Northern Great Plains	Wyoming	N. Mex.	Atlantic Coast	Gulf Coast	California
Plei.						Tulore f.
Pliocene	Ogallala gr.; Snake Creek beds		Sonto Fe		Citronelle f.	Son Joaquin f.; Etchegoin f.; Jocolitos f.
Miocen	Hemingsford gr.; Arikaree gr; Rose Bud		Sonto Fe	Yorktown f.; St Marys f.; Chaptank f.; Calvert f	Pascagaulo; Hattiesburg; Catahoula ss.	San Pablo gr (Monterey); Temblor f.
Oligocen	White River gr.: Brule clay; Chadron	Wiggins f.			Vicksburg gr.	Kreyenhagen sh.
Eocene		Uinto f; Bridger f; Green R; Wind R; Wasatch		Pamonkey: Woodstock; Aquio Gr f.	Jacksan gr; Cloiborne gr; Wilcox gr.	Kreyenhagen sh.; Domengine f.
Paleocene	Ft. Union gr.	Polecat Bench: Clark Fork f; Silver Coulee; Rock Bench f; ?; Montuo beds	Tiffany f; Torrejan f.; ?; Puerco f.		Midway gr.: Porters Cr. f; Cloytan f	Martinez gr.: Meganos gr

TABLE 11. Cenozoic Formations.

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